


# Presentation #1

- Given at the 11<sup>th</sup> International Mine Water Association Congress in Aachen, Germany, September 4-11, 2011
  - Johnson, Raymond H., 2011, Reactive Transport Modeling for the Proposed Dewey Burdock Uranium In-Situ Recovery Mine, Edgemont, South Dakota, USA. – In: Rüdé, R. T., Freund, A. and Wolkersdorfer, C. (eds.): Mine Water – Managing the Challenges. p. 221 – 225; Aachen, Germany  
[http://www.imwa.info/docs/imwa\\_2011/IMWA2011\\_Johnson\\_340.pdf](http://www.imwa.info/docs/imwa_2011/IMWA2011_Johnson_340.pdf)
- Also given at the 6<sup>th</sup> Uranium Mining and Hydrogeology Conference in Freiberg, Germany, September 18-22, 2011






Reactive Transport Modeling for  
the Proposed Dewey Burdock  
Uranium In-Situ Recovery Mine,  
Edgemont, South Dakota, USA

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## This presentation

- A series of conceptual models with working, but not fully quantitative 3D simulations (presented in 2D)

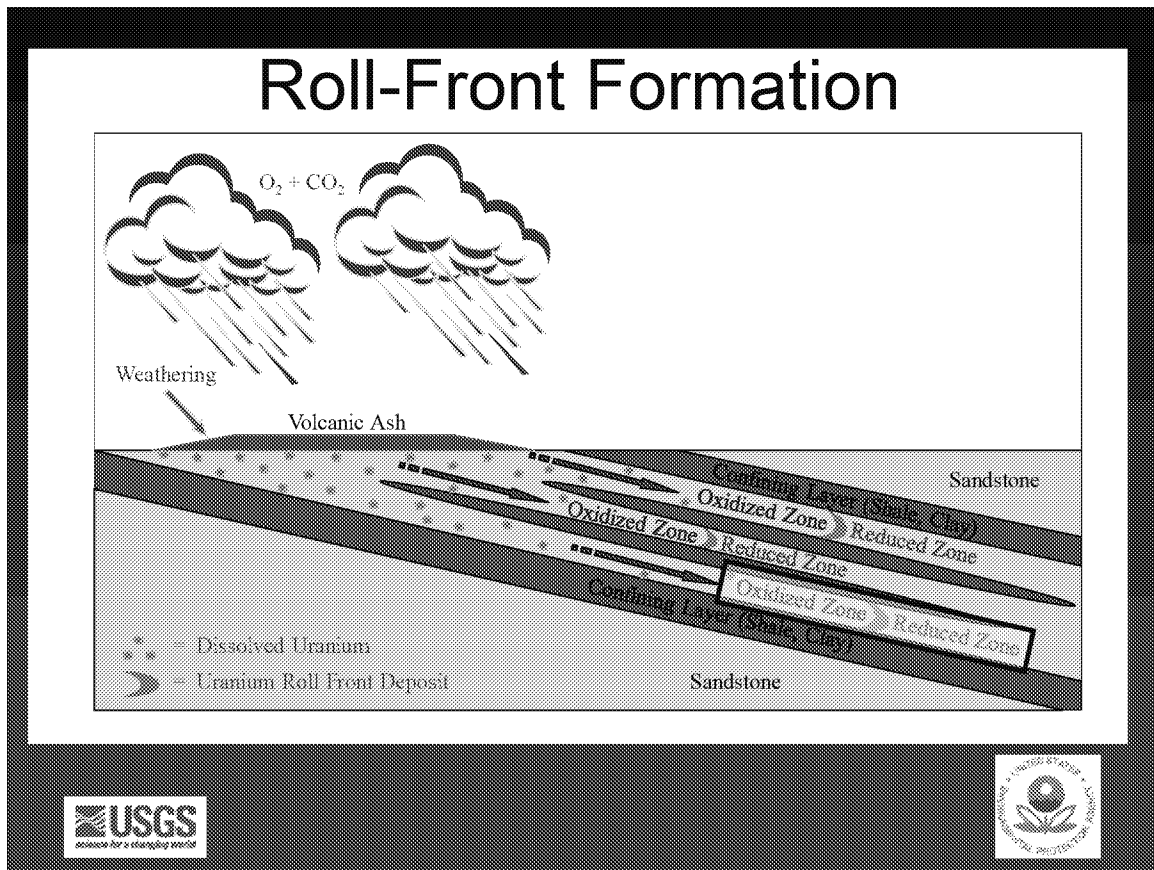


# Outline

- ISR basics
- Site details
- Reactive transport simulations
- Summary and conclusions



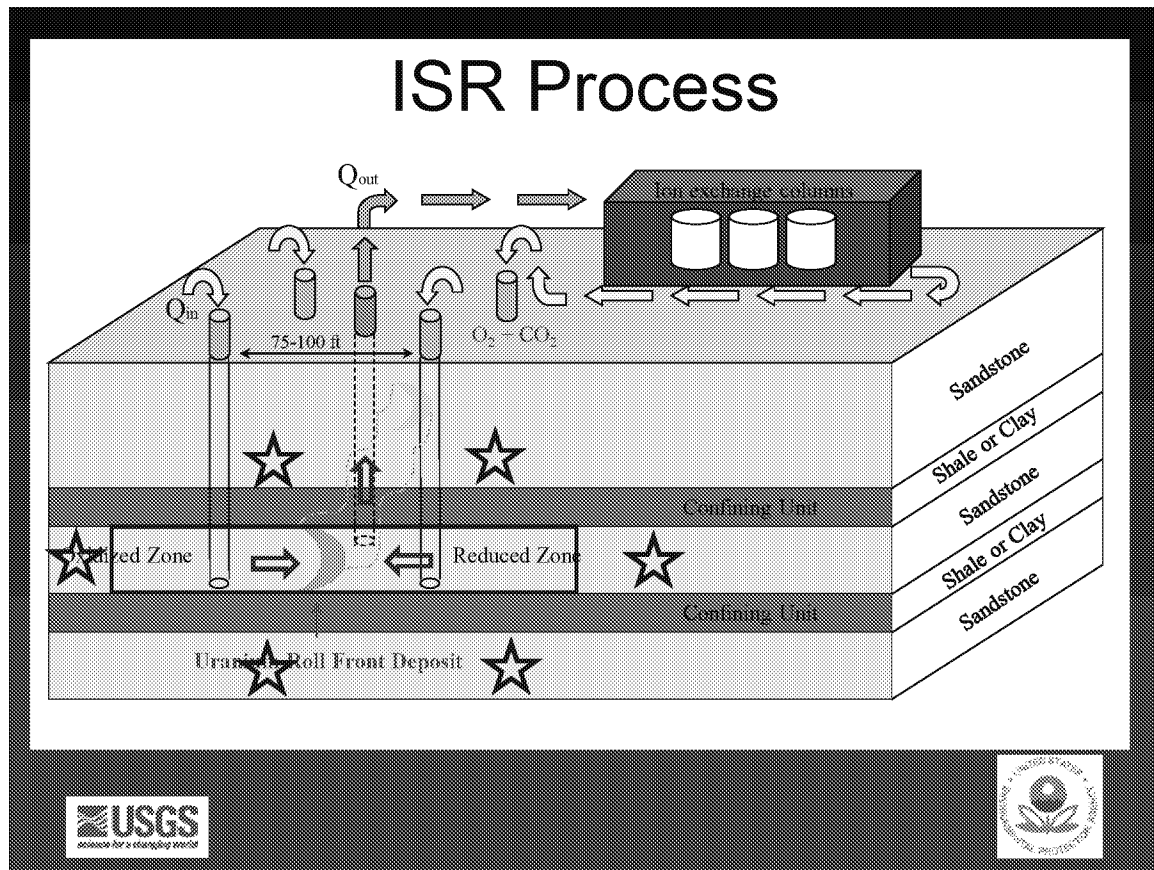




Uranium roll-front formation is often not in a single unit, but have stacked roll fronts, due to stratigraphy.

The black box conceptually indicates an area that is used for reactive transport modeling.

Uranium roll fronts occur at the oxidation/reduction interface because uranium becomes less soluble upon encountering reducing conditions.



This slide shows a typical five-spot well pattern. In three dimensions, the wells follow the uranium deposit.

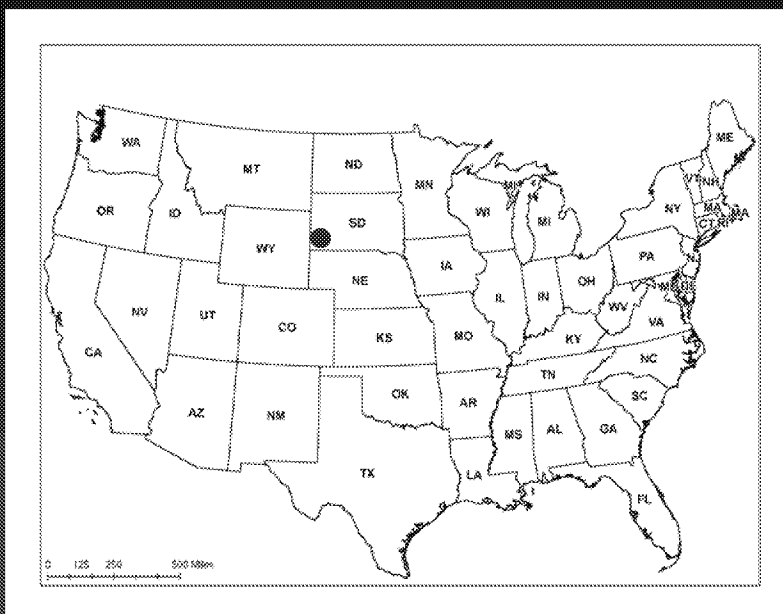
The blue box represents an aquifer exemption boundary. This boundary outlines a portion of the aquifer containing materials expected to be commercially producible.

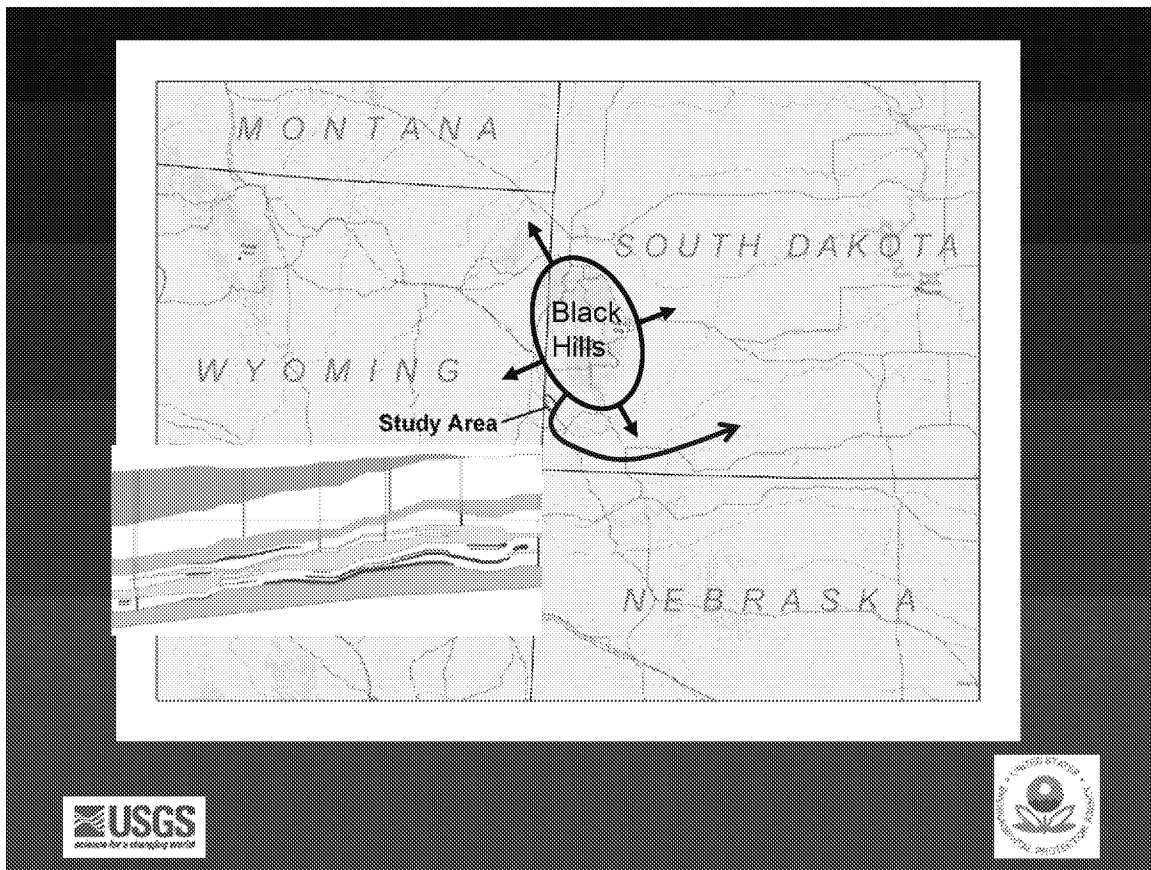
The goal with the final restoration process after uranium recovery is to get this zone (blue box) back to pre-mining groundwater quality.

The stars represent a typical monitoring well pattern surrounding the recovery zone and located in the nearest aquifers above and below the recovery zone.

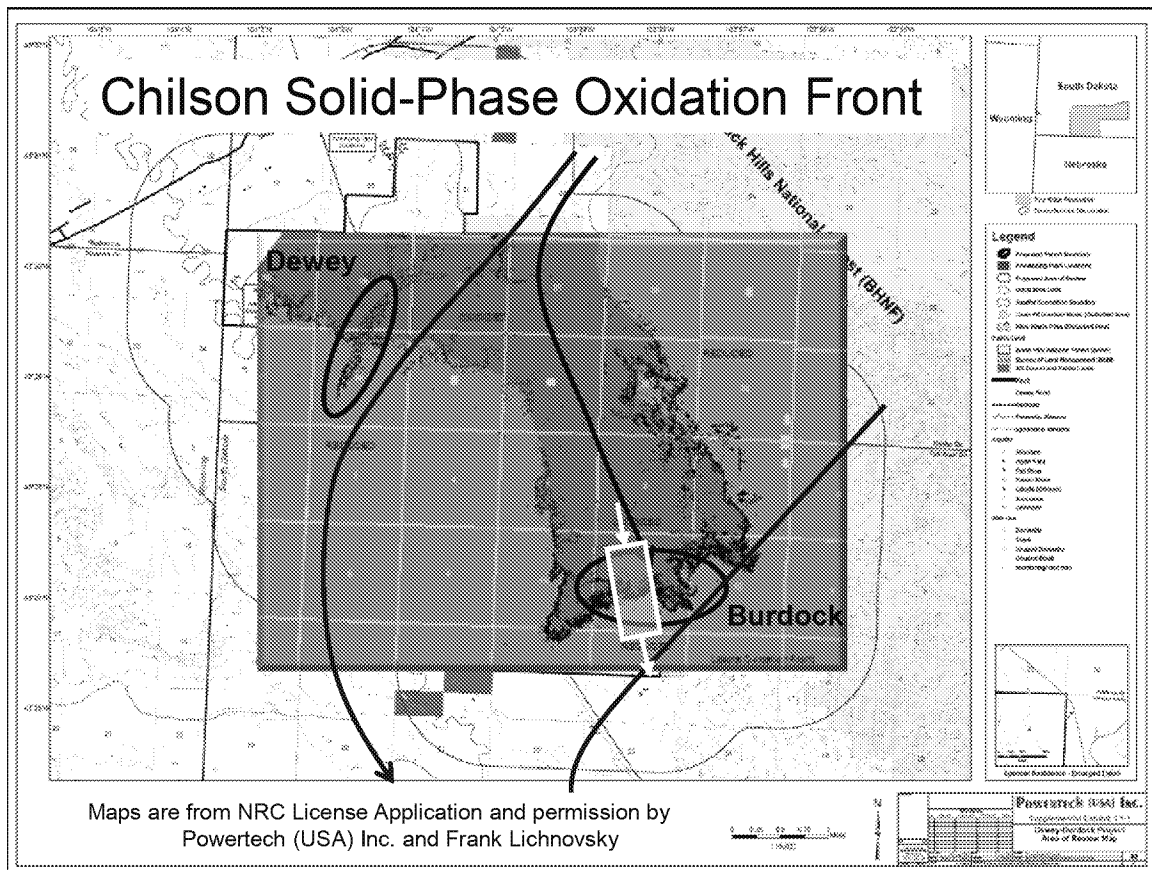
Ideally, these monitoring wells should never see any change in water quality.

## Dewey Burdock Site, South Dakota





The black arrows indicate dip of geologic layers away from the Black Hills uplift and the inset is a cross section (courtesy of Powertech (USA) Inc.) in the Burdock area. The blue arrow indicates regional groundwater flow down dip and then around the south end of the Black Hills.



Dewey and Burdock ore zones are circled in black. This map is only of the Chilson Member of the Lakota Formation.

The red color indicates oxidized solid phase and the gray color indicates reduced solid phase.

The black arrow in the middle indicates paleogroundwater flow that formed the uranium roll-fronts, which generally occur at the red/gray contact (redox front).

The blue arrows indicate current groundwater flow (approximately).

The white box with arrows is a representation of the model simulation area.

## Groundwater geochemistry

- Uranium remains relatively insoluble (40 ppb or less with little to no dissolved oxygen in the current groundwater)
- Uranium daughter products (like radon and radium) are greatest in the uranium ore deposits
- Roll fronts are not currently forming



The uranium roll fronts in the Dewey Burdock area moved approximately down stratigraphic dip in the past. However, current groundwater flow is not in the same direction, resulting in the consumption of oxygen in a different location. The roll fronts today are not currently moving because of this lack of oxygen in the groundwater.

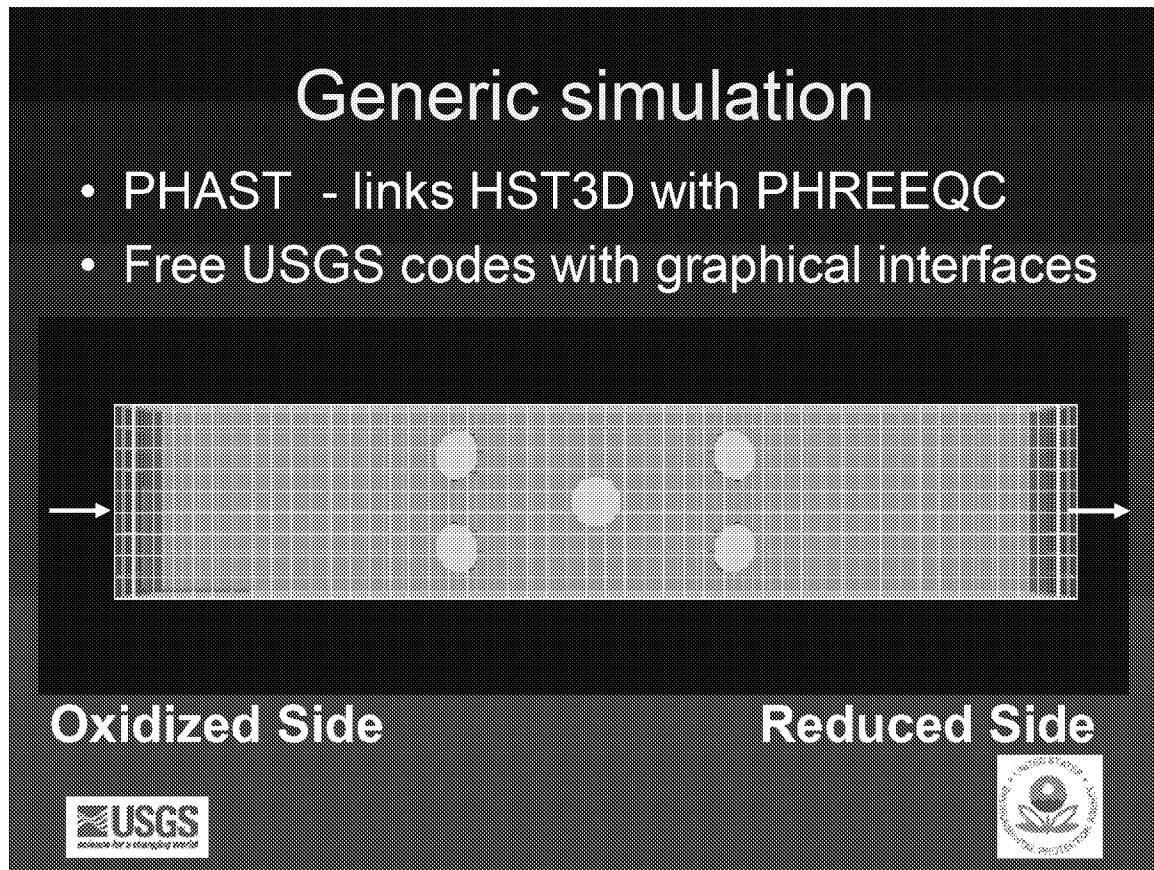
## Reactive transport modeling

- Links groundwater flow and geochemistry
- Can we quantify groundwater flow and geochemistry before, during, and after mining?
- Can we predict long-term influences on groundwater quality?



This presentation is the initial step in understanding possible quantitative predictions and how well they can be used.

The main questions in this research are 1) what do we have (tools and data), and 2) what do we need to make quantitative predictions.



PHREEQC is a geochemical modeling code developed by the USGS ([http://wwwbrr.cr.usgs.gov/projects/GWC\\_coupled/phreeqc/](http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/)).

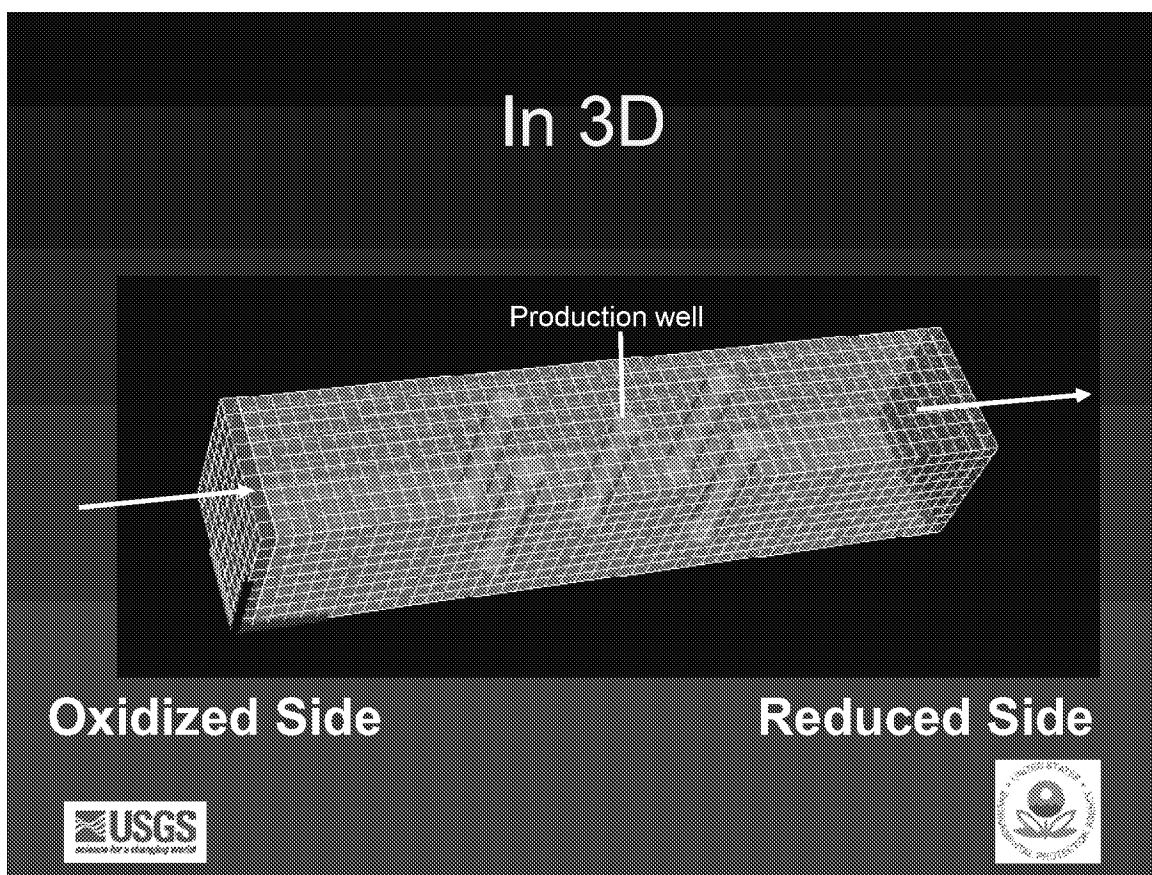
PHAST is a reactive transport code

([http://wwwbrr.cr.usgs.gov/projects/GWC\\_coupled/phast/](http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phast/)) which couples groundwater flow (HST3D) simulations and PHREEQC.

Numerical dispersion can be a problem with PHAST and will be seen in the subsequent slides.

Box diagram is a screen capture of the PHAST simulation, which is a three-dimensional box with 1 m cells (10 by 50). This slide is in plan view and will be the same view in modeling results slides. Yellow dots indicate injection wells (four outside wells) and one production well (center well). The arrows indicate groundwater flow from left to right and the oxidation front will proceed from left to right as oxygen and uranium are introduced into the left side. The whole domain is originally a reduced solid phase.





Same model domain as previous slide, but seen in three dimensions (3D). This is a typical five-spot well production pattern and wells are screened throughout the domain.

## Simulations

- Uranium roll-front formation
- Current groundwater
- ISR Mining
- Restoration (1 - with DO, 2 - no DO)
- Return to natural groundwater flow conditions (considering 1 and 2 in restoration)



All simulations do not include diffusion or dispersion, but numerical dispersion does occur.

DO = dissolved oxygen.

In the first three simulations, dissolved oxygen is variable and is included and discussed as part of the simulation.

## Uranium Roll-Front Formation

- Start with pyrite everywhere
- No uranium in solid phase
- Introduce groundwater with dissolved oxygen and uranium (left side)
- Allow uraninite precipitation and pyrite dissolution
- Use chloride as a tracer



All simulations are still conceptual in nature, so amounts of pyrite, oxygen, etc. are not quantitative.

## In slide animations

- Time is generic!
- There is numerical dispersion!
- Red = high concentration
- Blue = zero concentration

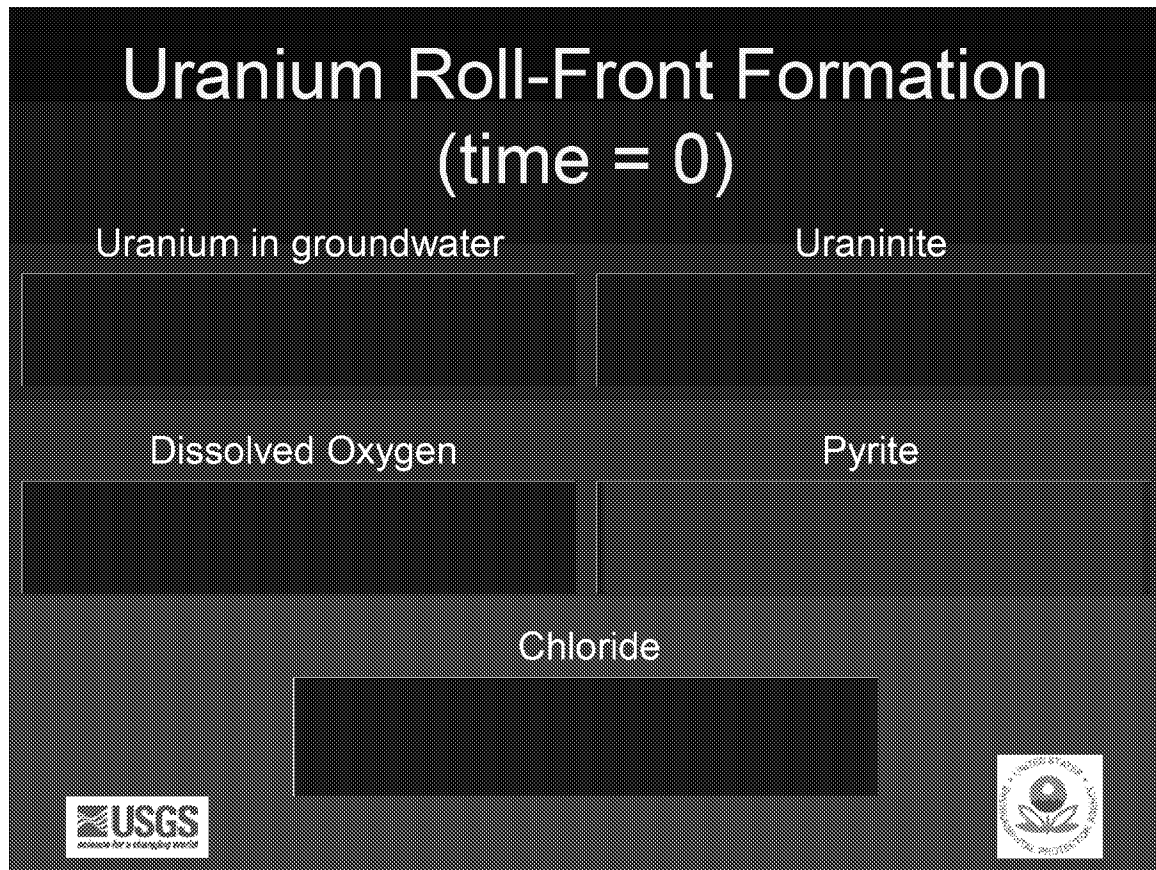


Again, geochemical quantities (pyrite, oxygen, groundwater concentrations, etc.) are also generic.

Numerical dispersion is dispersion that is created by the modeling code (PHAST in this case) due an imbalance in time stepping and cell sizes.

Shorter time steps and smaller cell sizes can reduce dispersion, but was not investigated in detail at this conceptual stage.

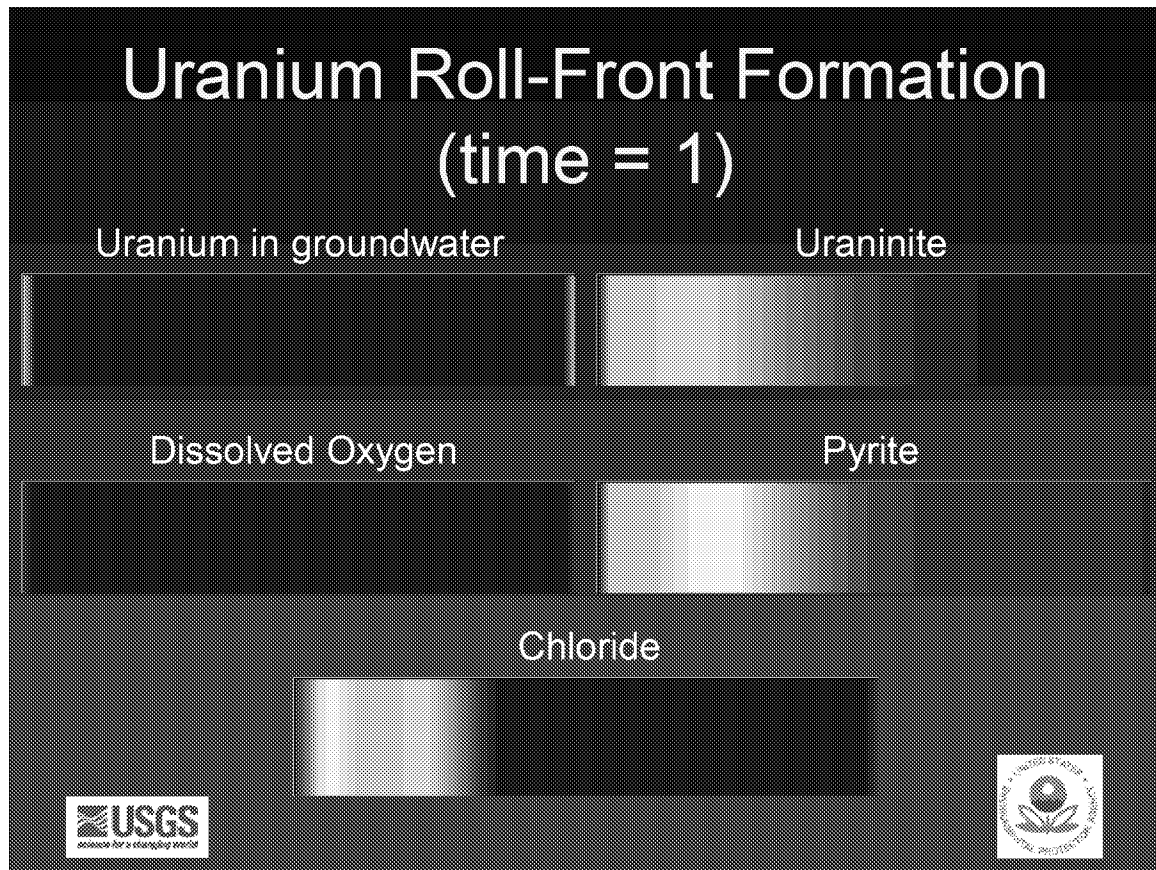
In reality, some dispersion would be anticipated.



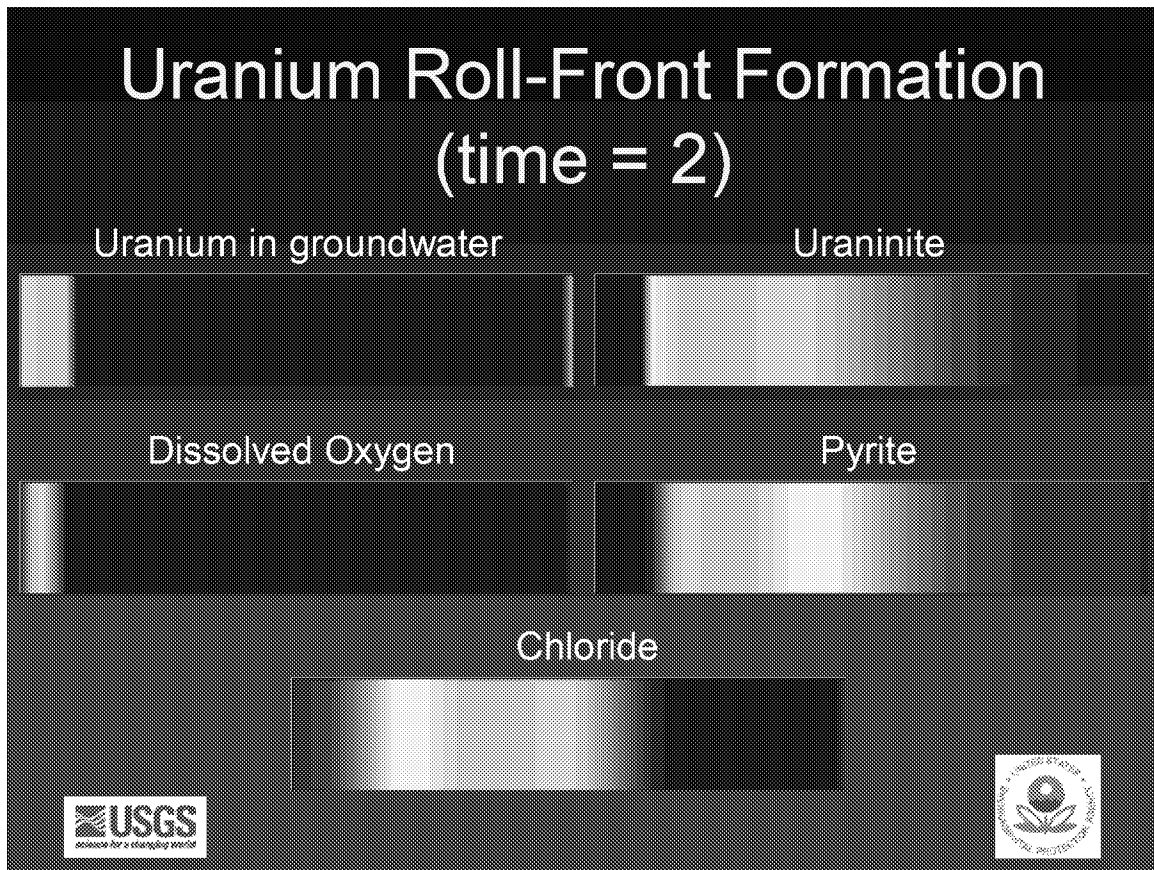
This slide represents conditions before any inflow to the system. All groundwater and solid phase material are reduced and pyrite is stable.

In this and all subsequent slides, groundwater flow is always from left to right.

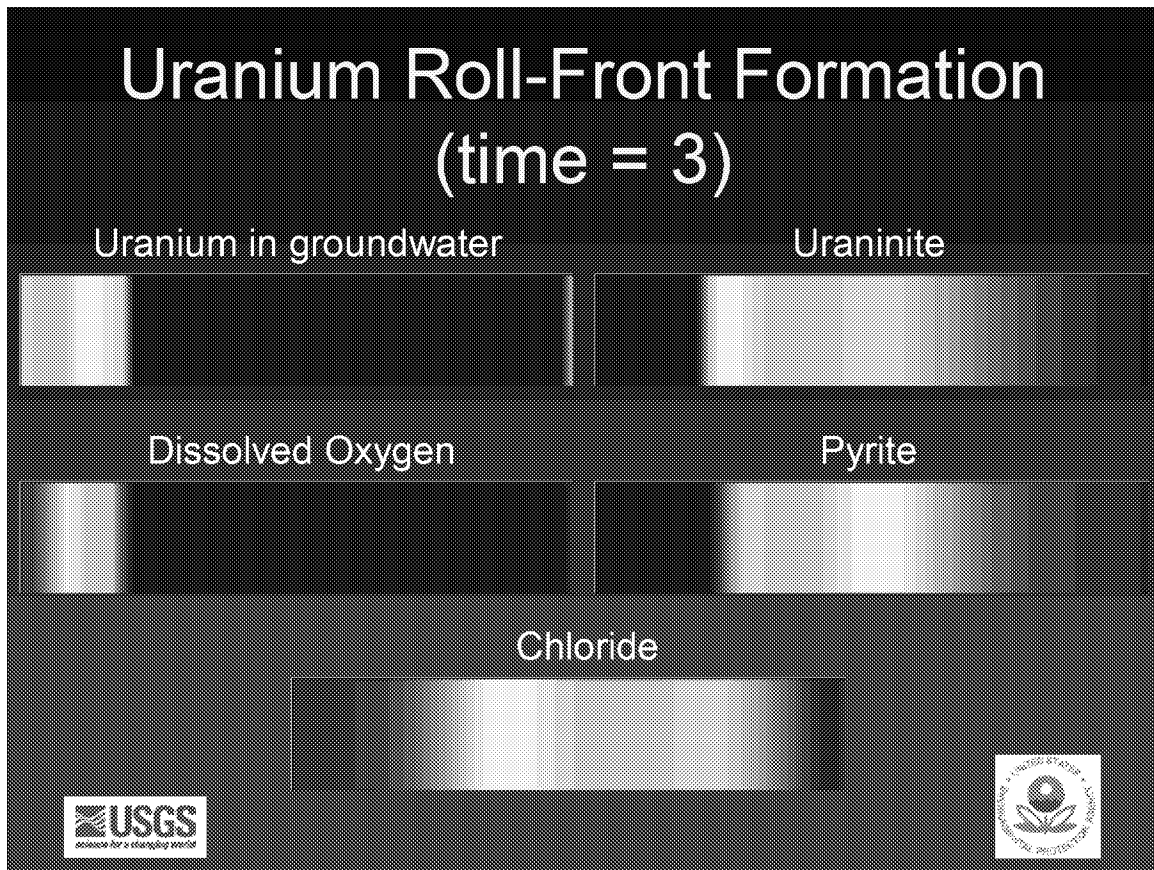
In this and all subsequent slides, uranium, dissolved oxygen, and chloride are dissolved in the groundwater, and uraninite and pyrite are the associated solid phases in the corresponding locations.



Uranium and dissolved oxygen are introduced on the left side into the aquifer, which results in pyrite oxidation and the precipitation of uraninite. As a result, the uranium and DO front do not move as quickly as the conservative chloride tracer. Chloride would not actually be an input in a real system, but is used here just for comparison of natural groundwater flow rates.

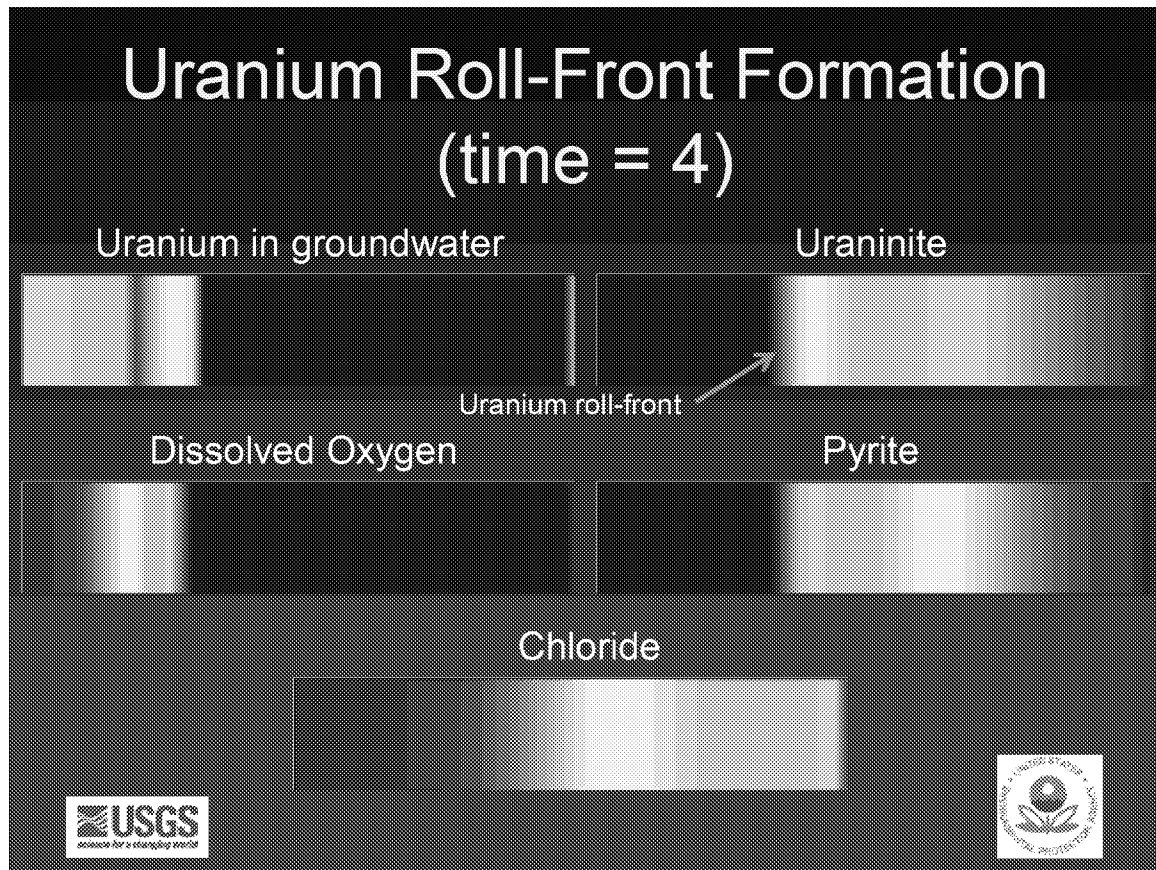


Same comments as slide #18.



Same comments as slide #18.





Same comments as slide #18.

The difference in movement of chloride compared to uranium and DO is quite apparent. This shows the oxidized side of the roll front to the left and the remaining reduced side on the right.

This series of slides shows how the uranium in the groundwater is removed from solution, precipitated as uraninite, and forms the uranium roll front.

## Current Groundwater

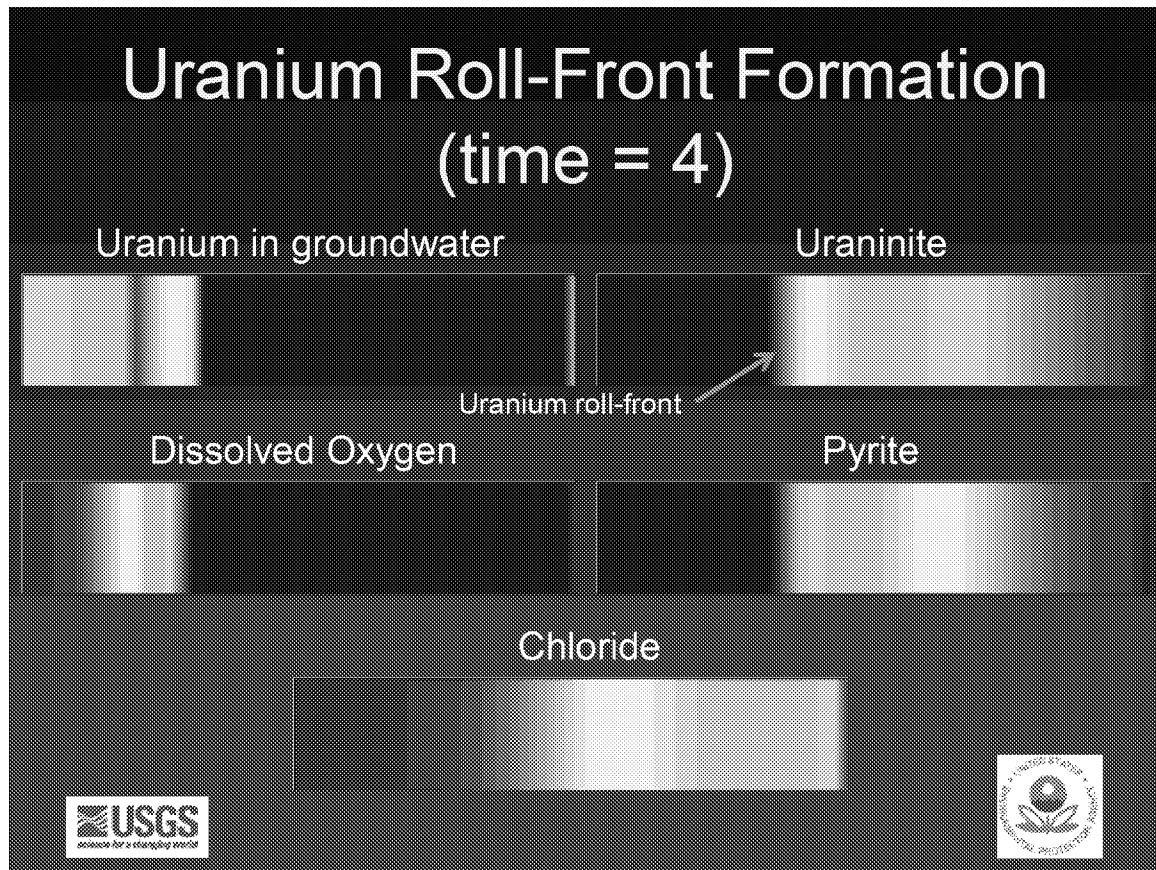
- Use “background” groundwater
- High calcium and sulfate
- No dissolved oxygen
- Note that “leftover” dissolved oxygen moves roll-front slightly
- Use a no-chloride tracer



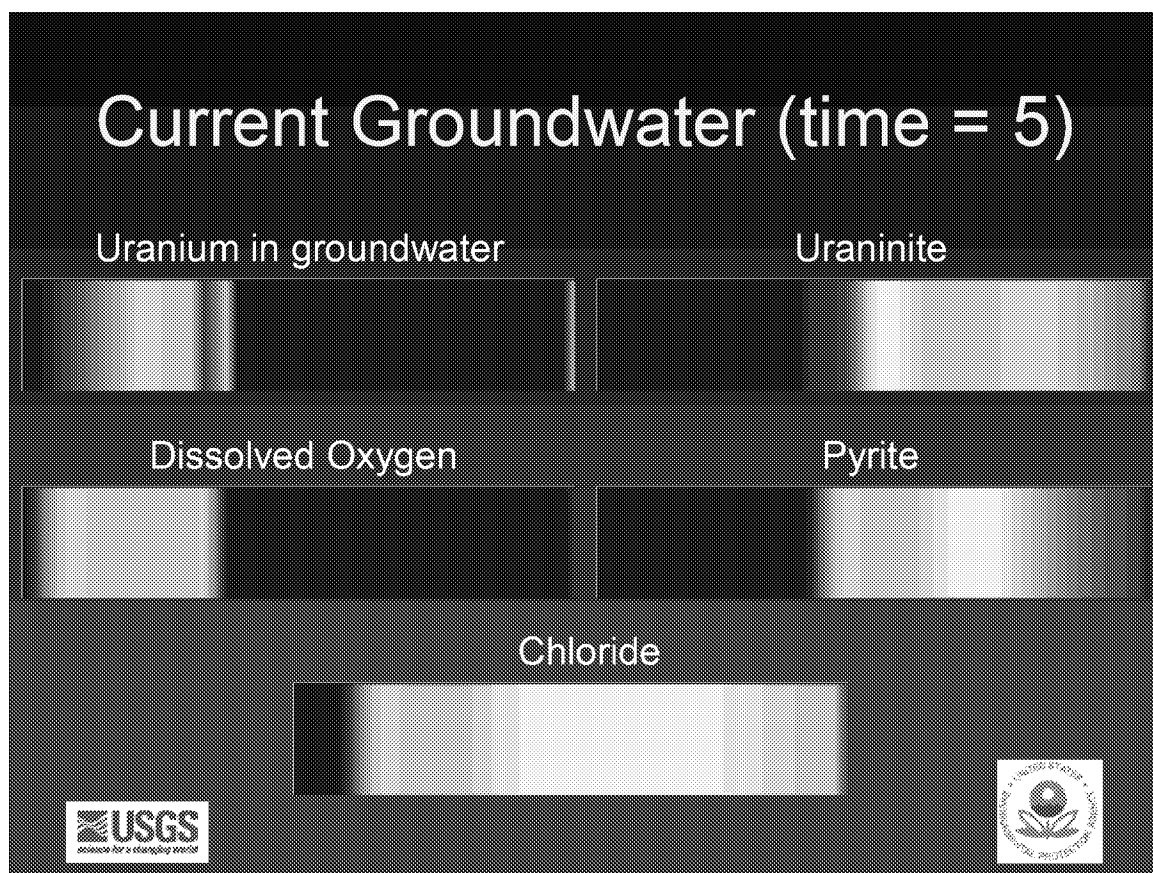
Background groundwater is the concentrations currently observed in groundwater before it enters the current uranium ore zone.

The “leftover” dissolved oxygen is a function of the simulation time between the end of the roll front formation and current conditions.

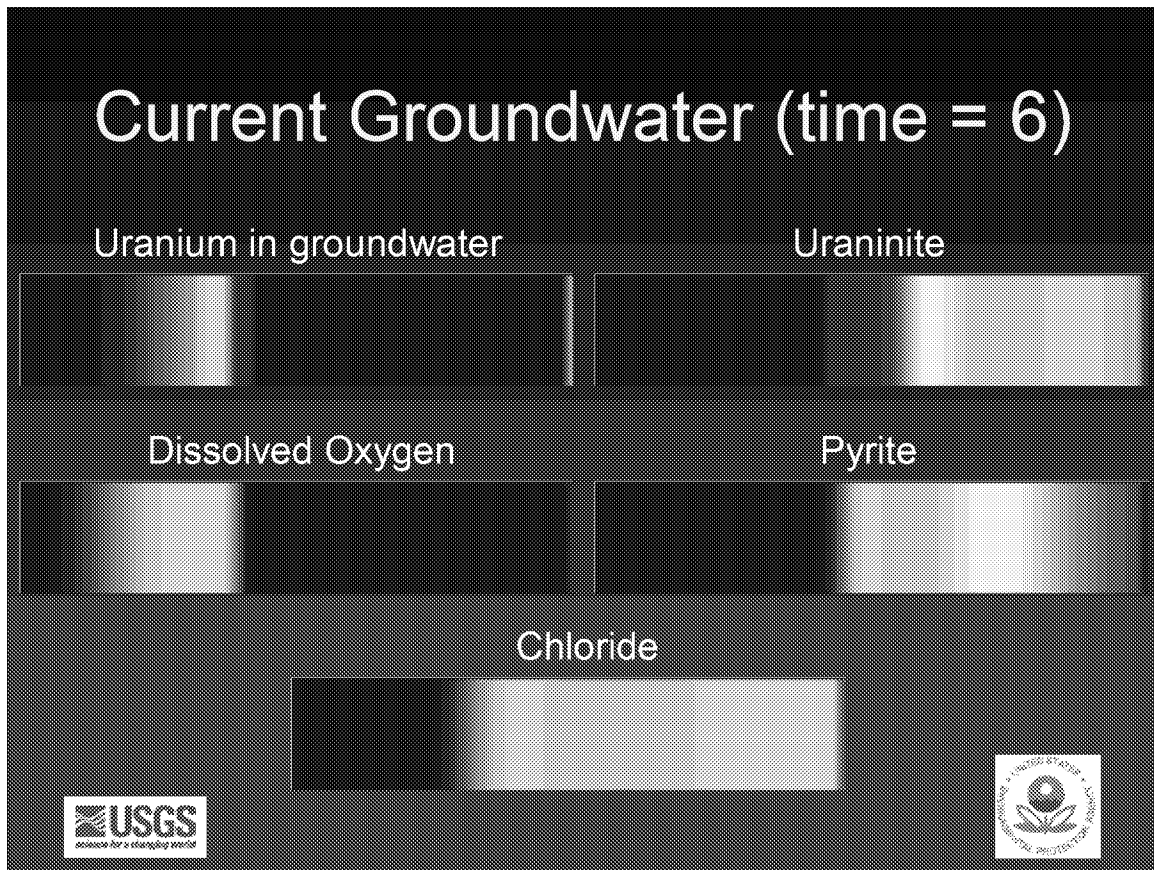
Chloride is no longer injected on the left side.



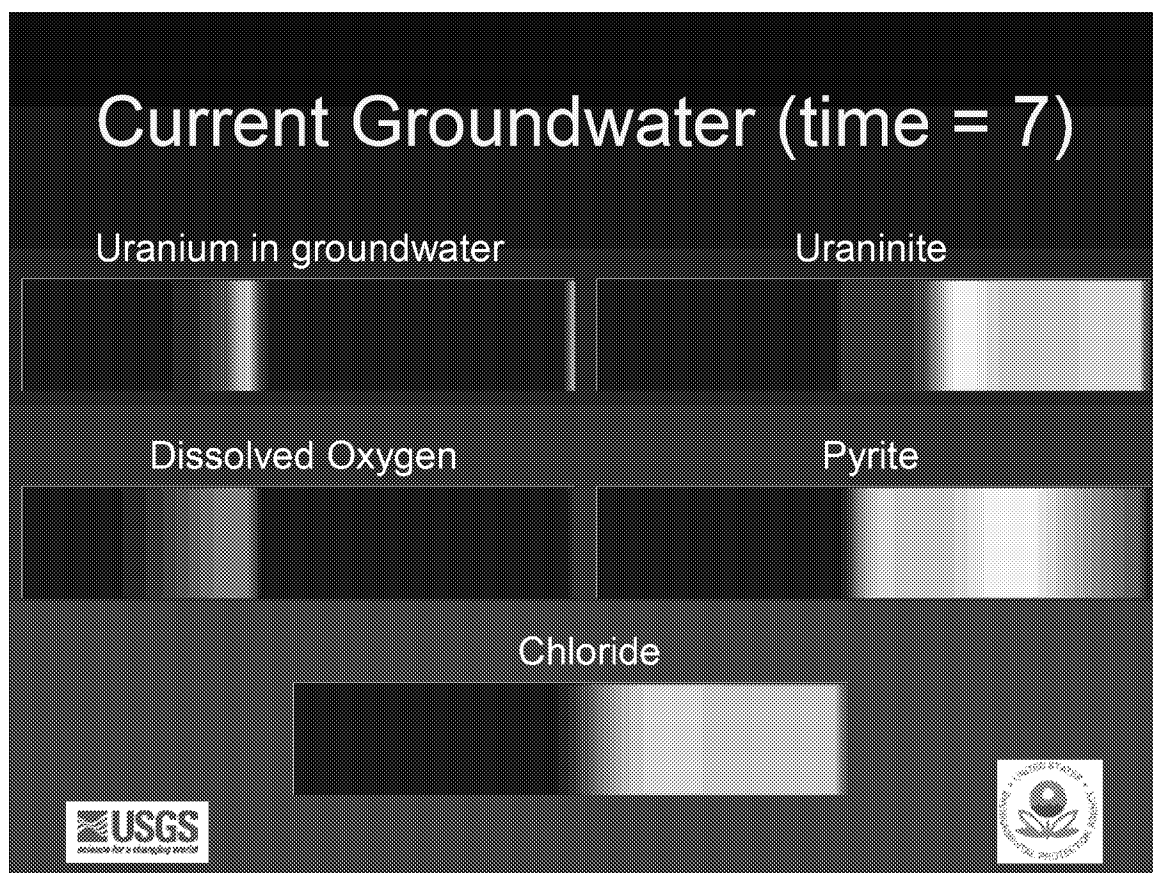
Reminder on where we left off.



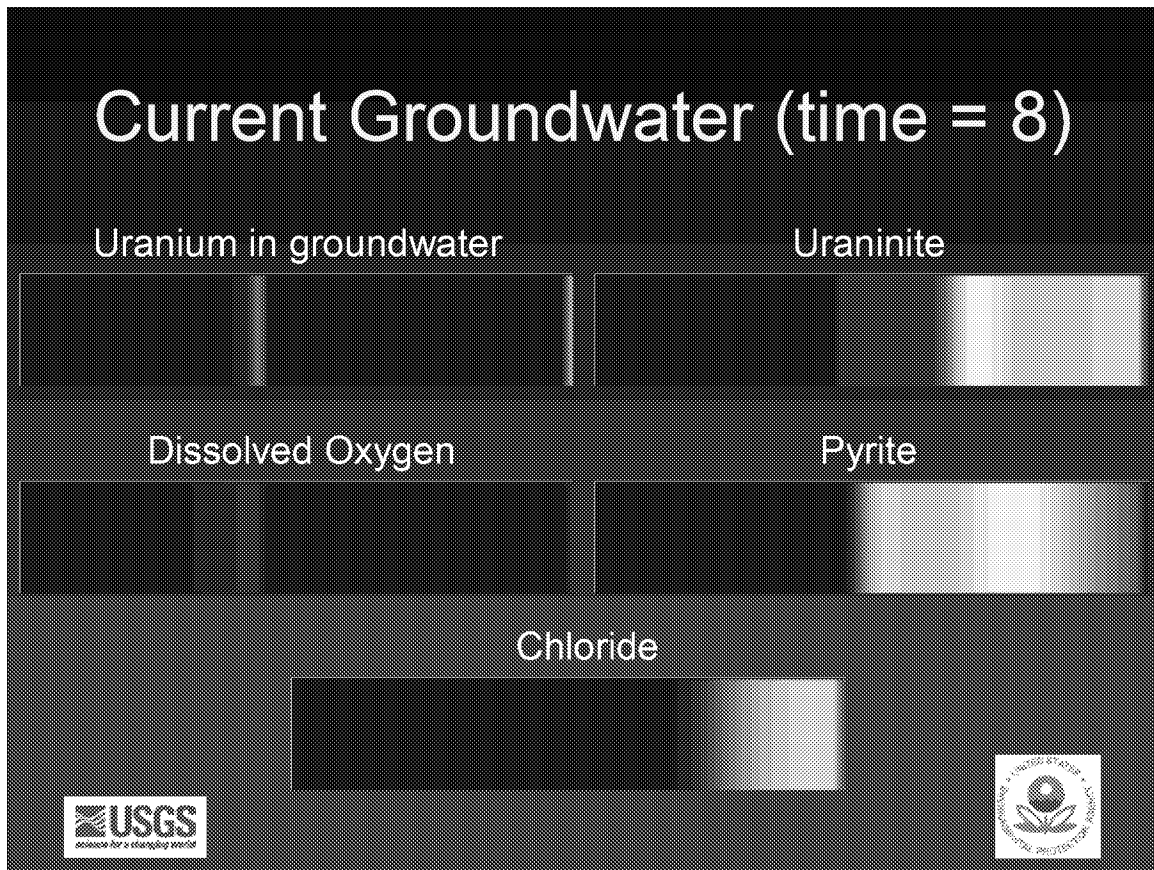
The slides in this series “lead up to” current groundwater conditions by precipitating the “leftover” uranium as uraninite along with the consumption of oxygen and pyrite, while the reduction in chloride content indicates the groundwater flow rate. All of this comes about due to a change in the direction of groundwater flow at the site (not seen in the simulations). Note that uranium and dissolved oxygen are no longer entering the system.



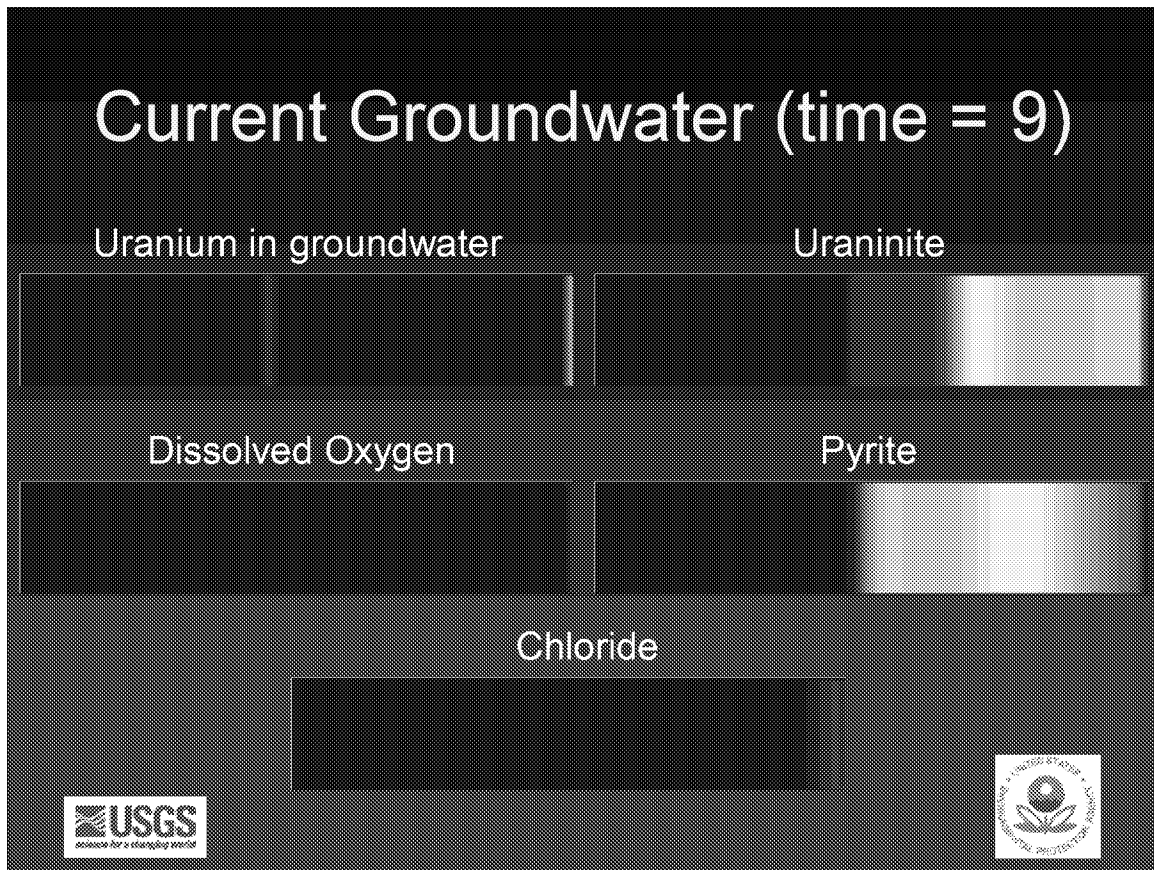
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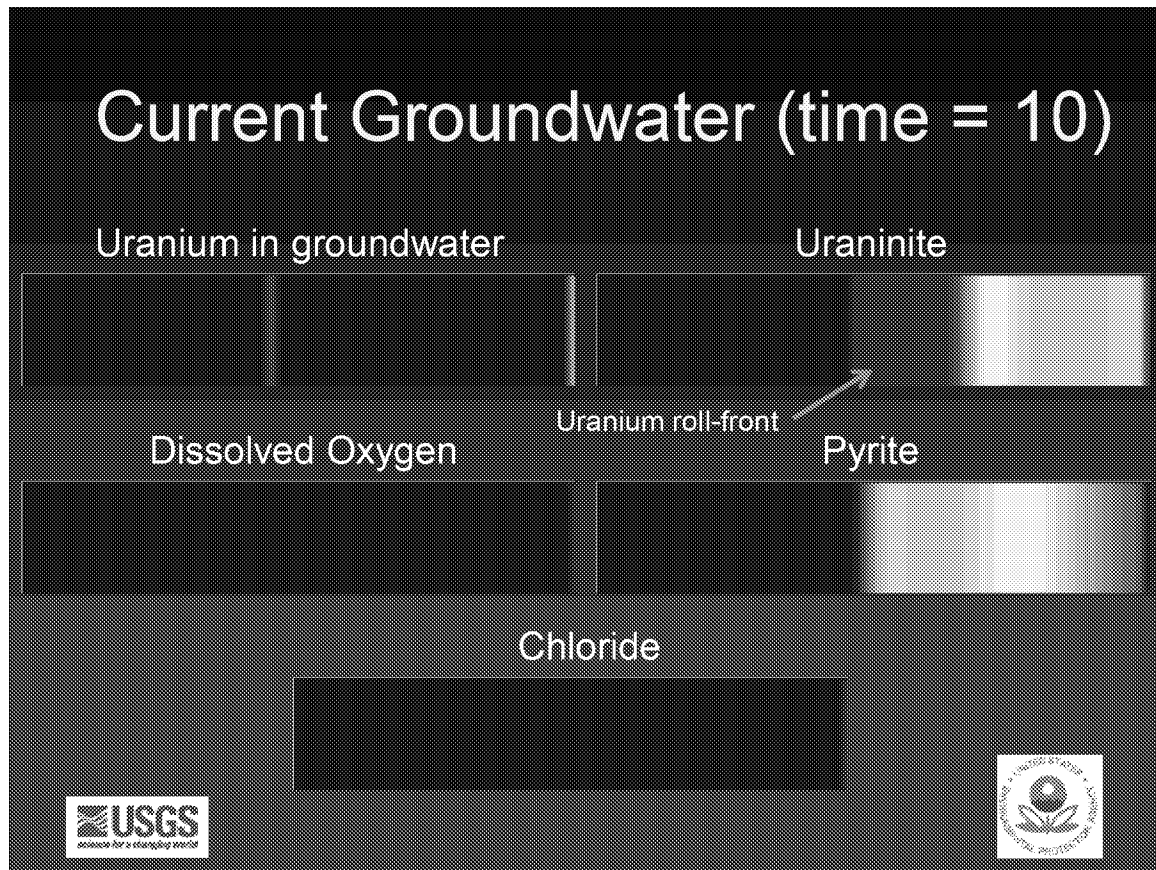


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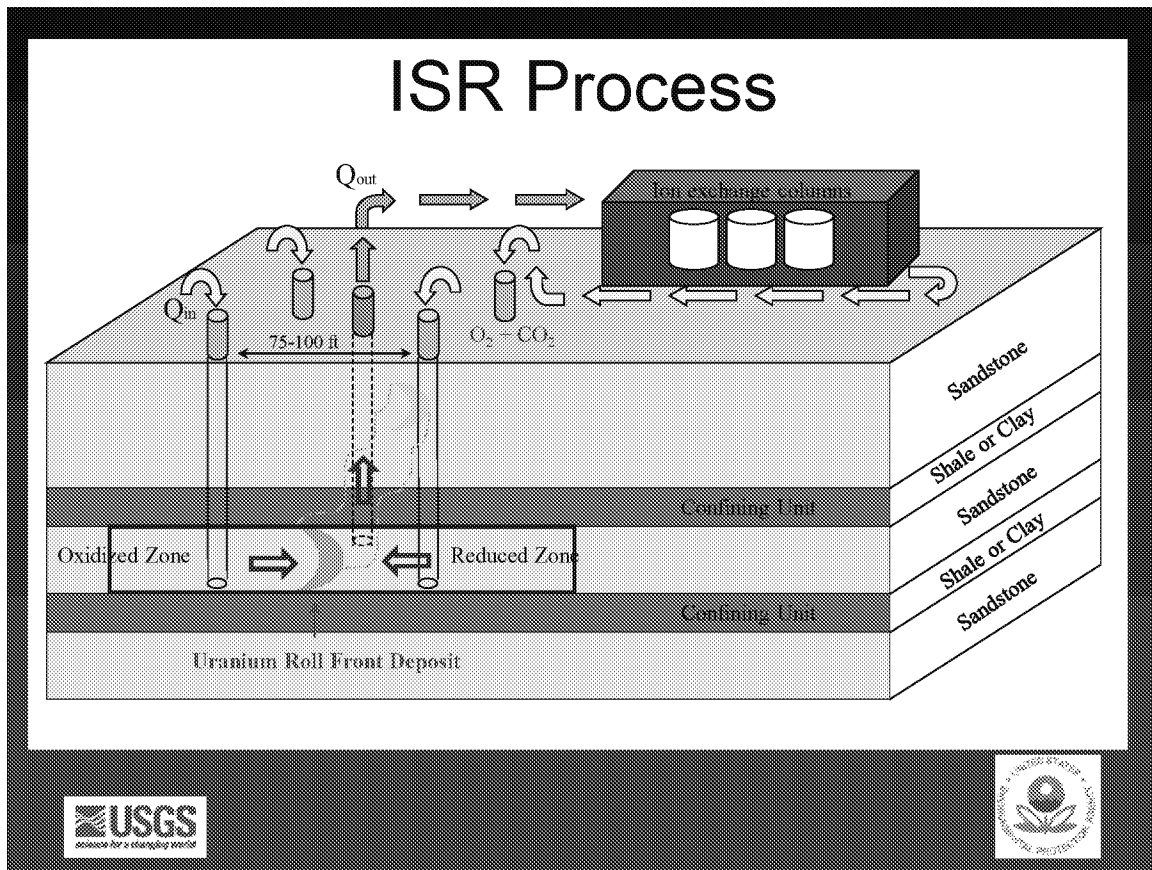
This is present day conditions, with no uranium in the groundwater, since the change in groundwater flow direction (again, at the site, not seen in the simulations) results in the lack of oxygen entering the simulation domain. This lack of oxygen means that uranium is not mobile and the pyrite and uraninite remain stationary at the ore zone and the downgradient reducing zone. Roll-front is in the center of the rectangle.

## ISR Mining

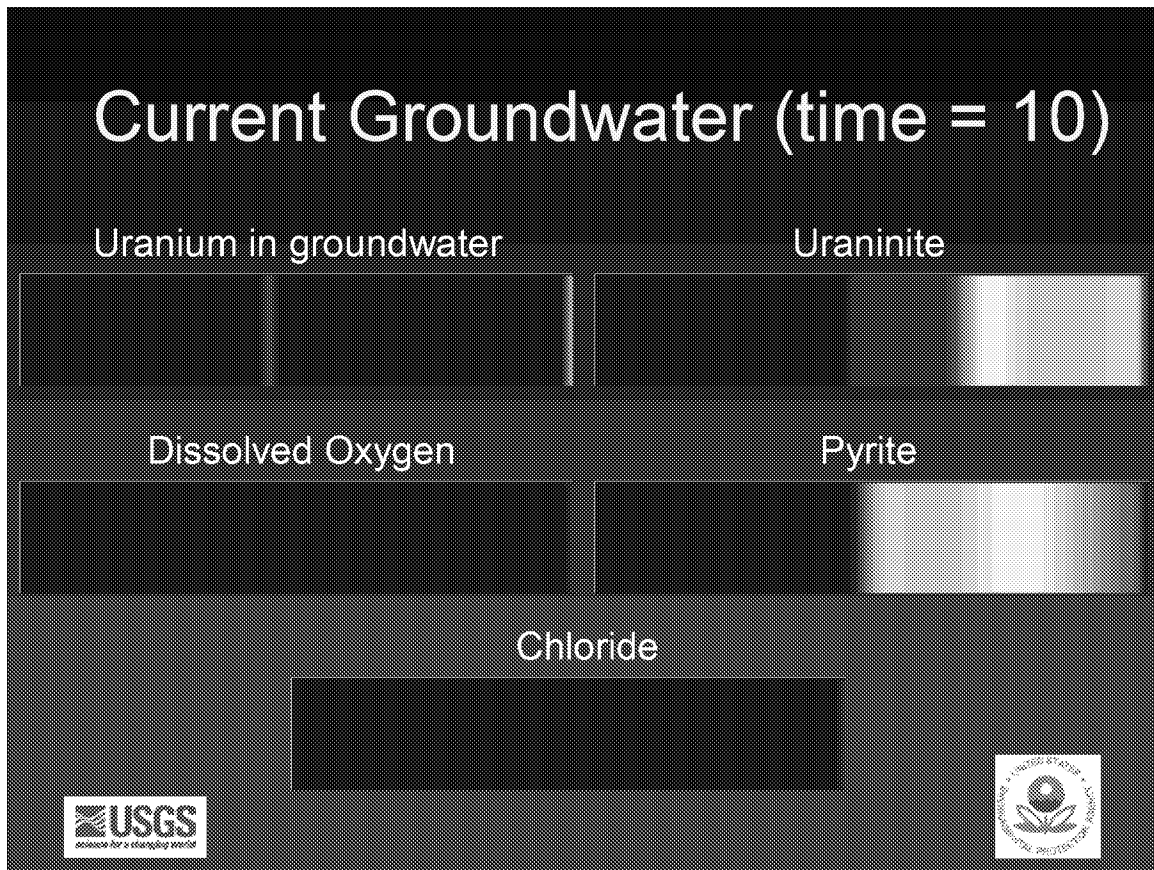
- Lixiviant with high dissolved oxygen and dissolved carbon dioxide (pH = 6)
- Uranium at 50 ppb (in lixiviant at injection)
- High chloride content



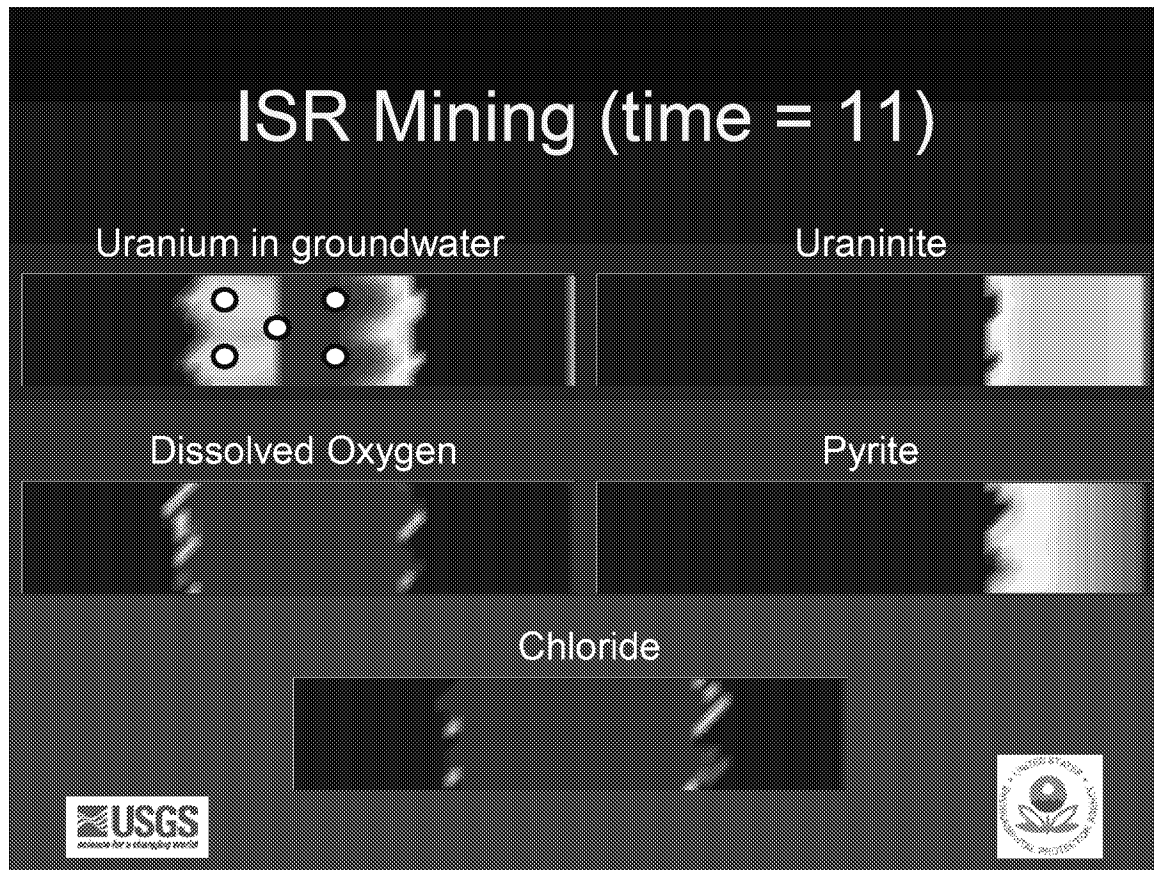
Again, geochemical concentrations are generic, although specific values need to be put into the simulation (like 50 ppb for uranium).



Reminder of the zone we are looking at.  
Note 3D outline of uranium roll front. 2D simulations are actually a plan view or view from the top.



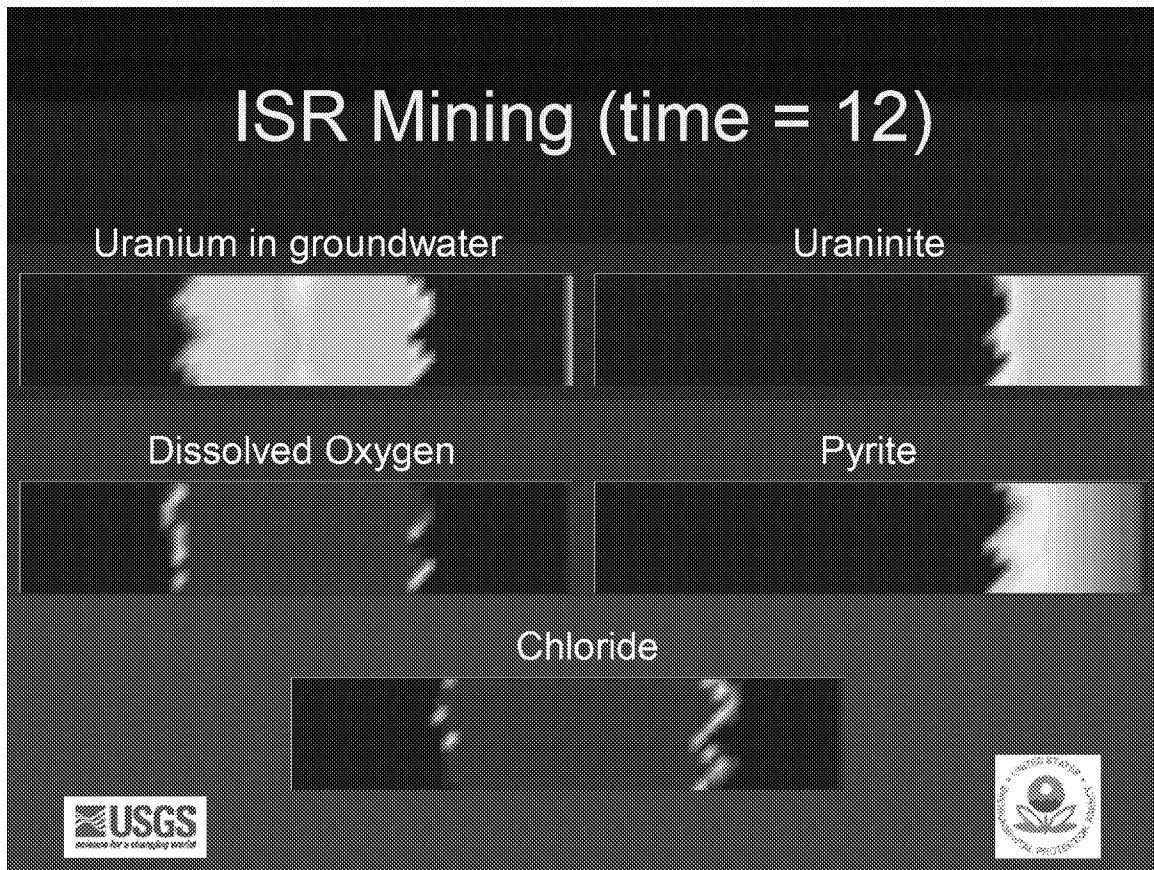
Reminder on where we left off.



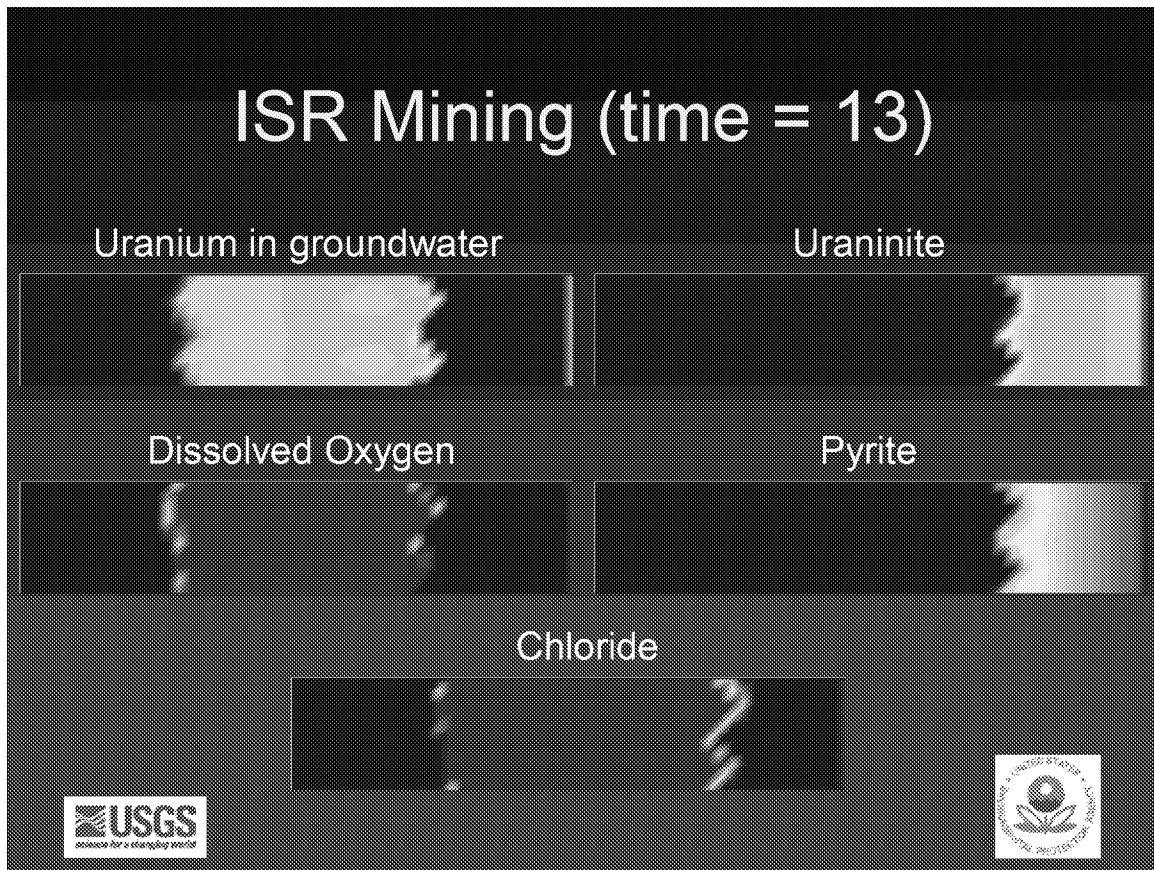
This slide takes the previous time=10 (pre-mining conditions) and “turns on” a five-spot well pattern for uranium recovery.

The edge of the oxidation/reduction zone in time=10 was located at the center well. The center well is production and the surrounding wells are injection.

The mobilization and recovery of uranium can be seen in the high uranium concentration (red) in the zone where high uraninite occurred (time=10). In this simulation, the injection wells on the left side are not providing any uranium recovery because they were too far from the ore zone. The circulation of lixiviant provides high DO and chloride throughout the production zone. The high dissolved oxygen results in the removal of uraninite and pyrite. Note that in reality, high chloride contents in the lixiviant are a result of using chloride to regenerate the ion exchange resins.



Once the uraninite is removed, the uranium concentrations go down to approximately 50 ppb (the value entered for barren lixiviant).



Same comment as slide #35.

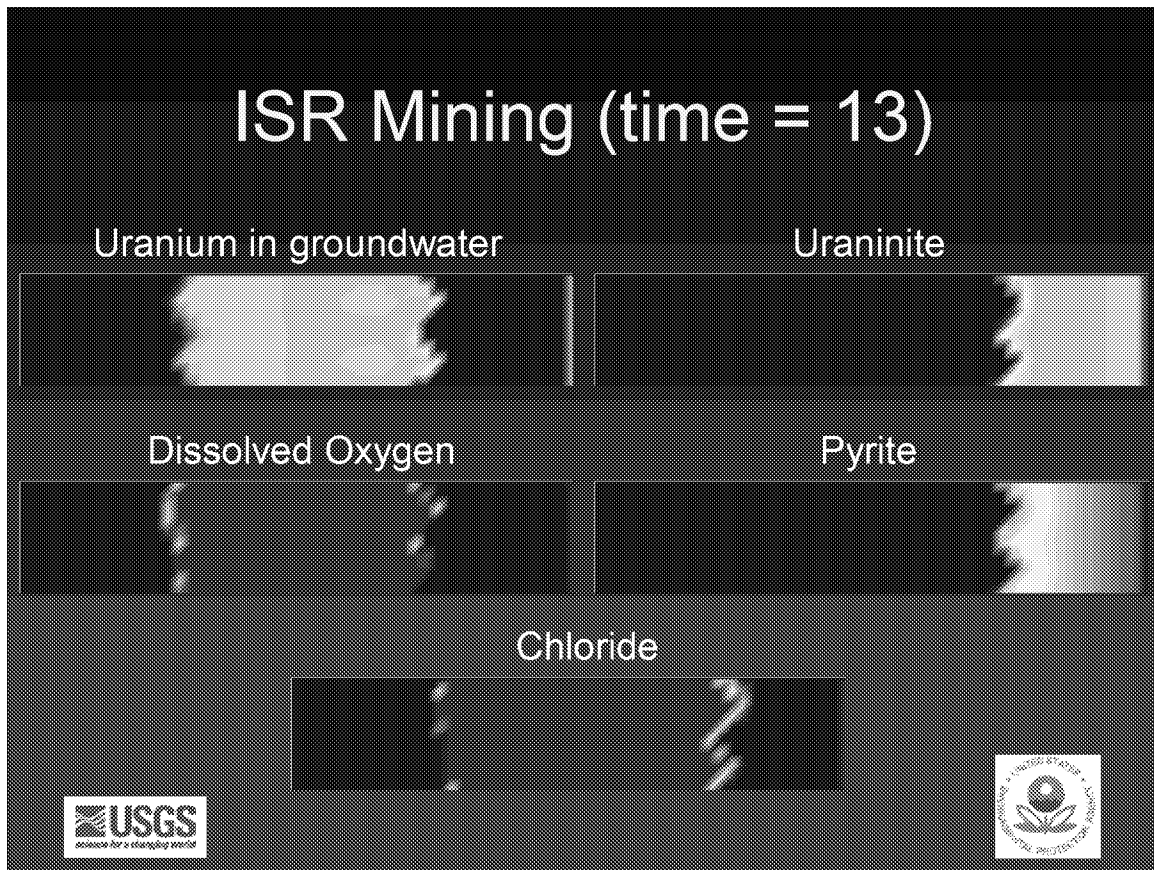
## Restoration

- Flush out mining zone (again, some numerical dispersion)
- Recirculate through a reverse osmosis unit
- Low concentrations of everything
- Uranium kept at 50 ppb
- No chloride
- NO oxygen control

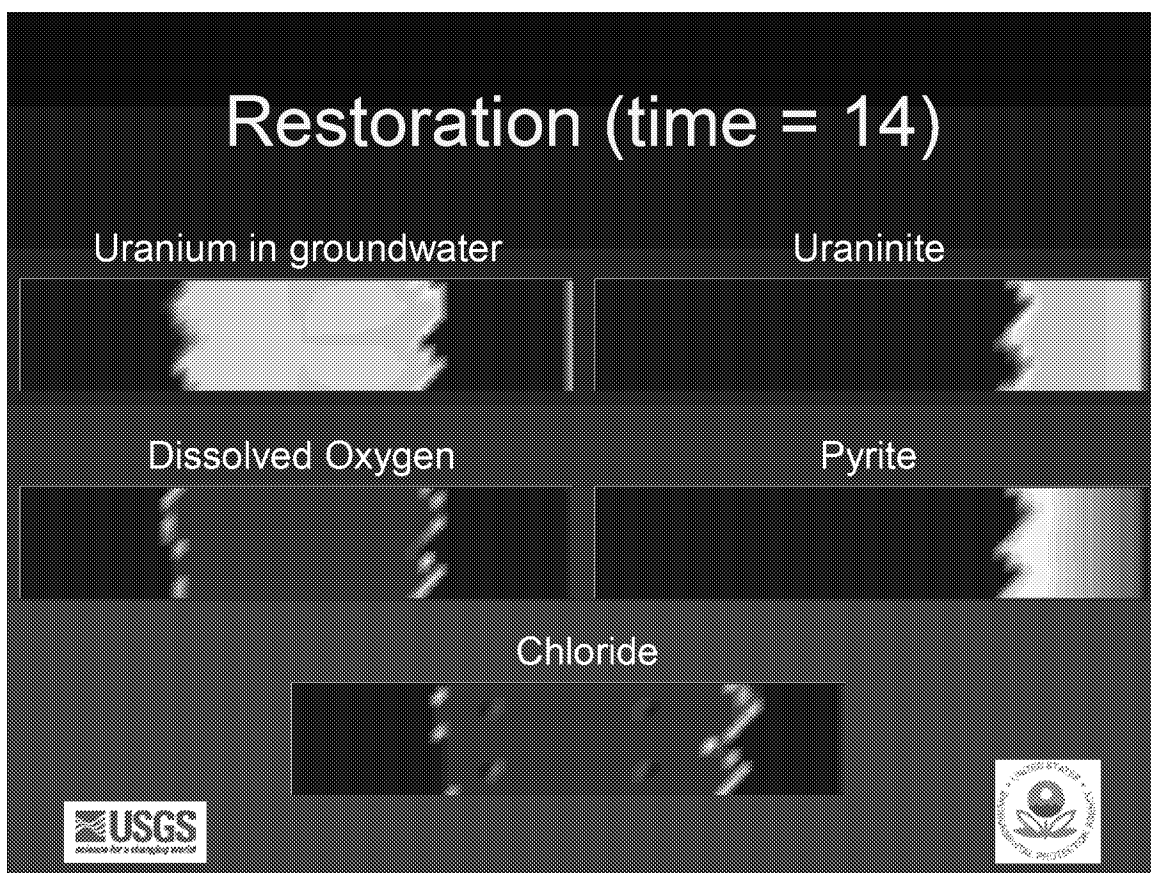


No oxygen control indicates that the restoration fluids are allowed to equilibrate with the atmosphere (results in approximately 8 mg/L oxygen in solution).



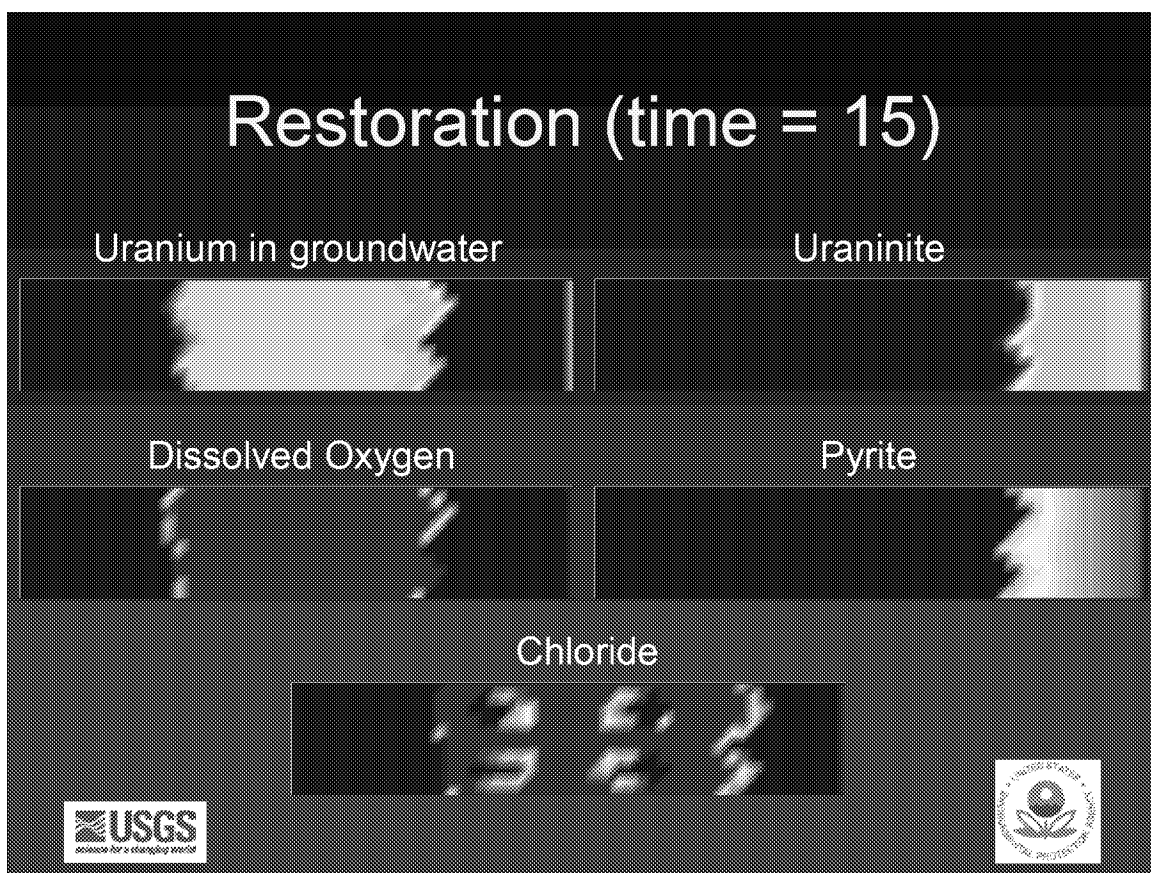


Reminder on where we left off.

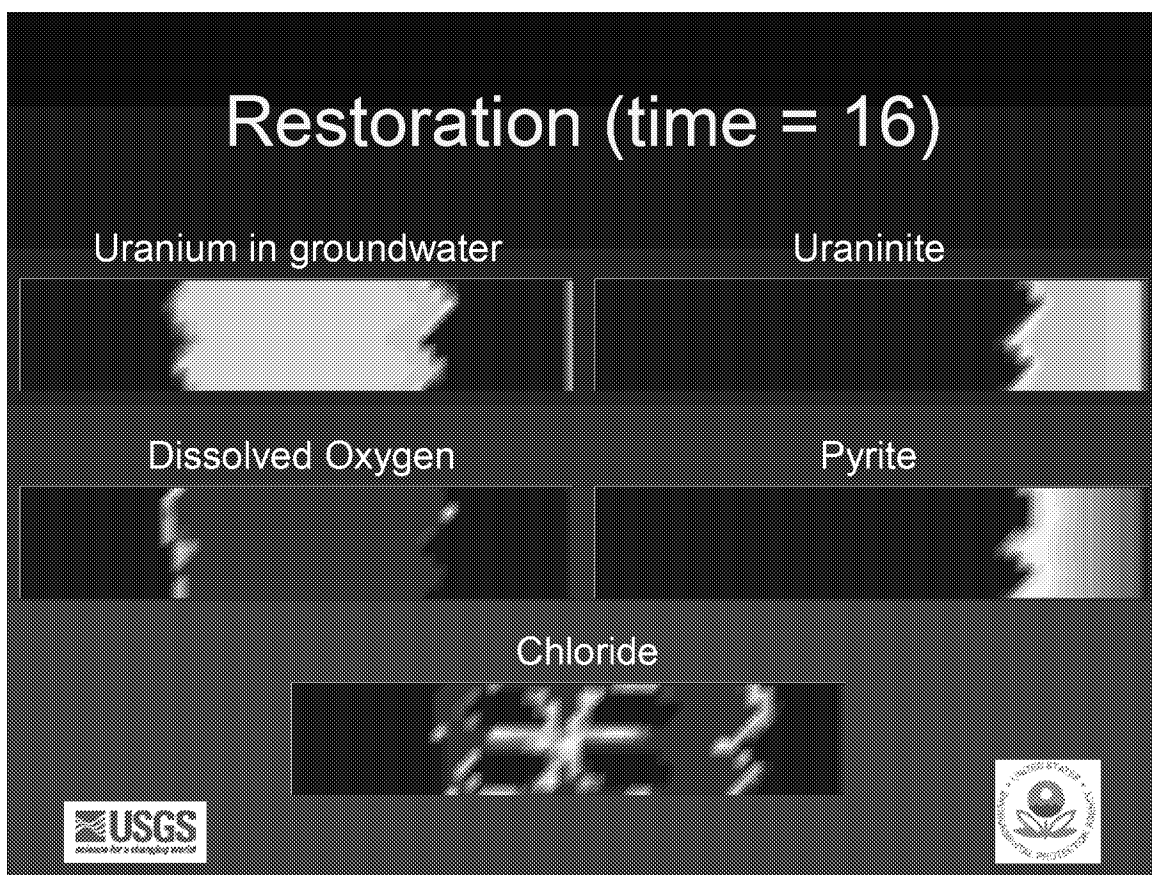


Start to see four-spot pattern in chloride as the injection wells inject restoration fluid with no chloride.

This does not happen for DO because it remains at 8 mg/L.



Injection of “clean” restoration fluid continues.



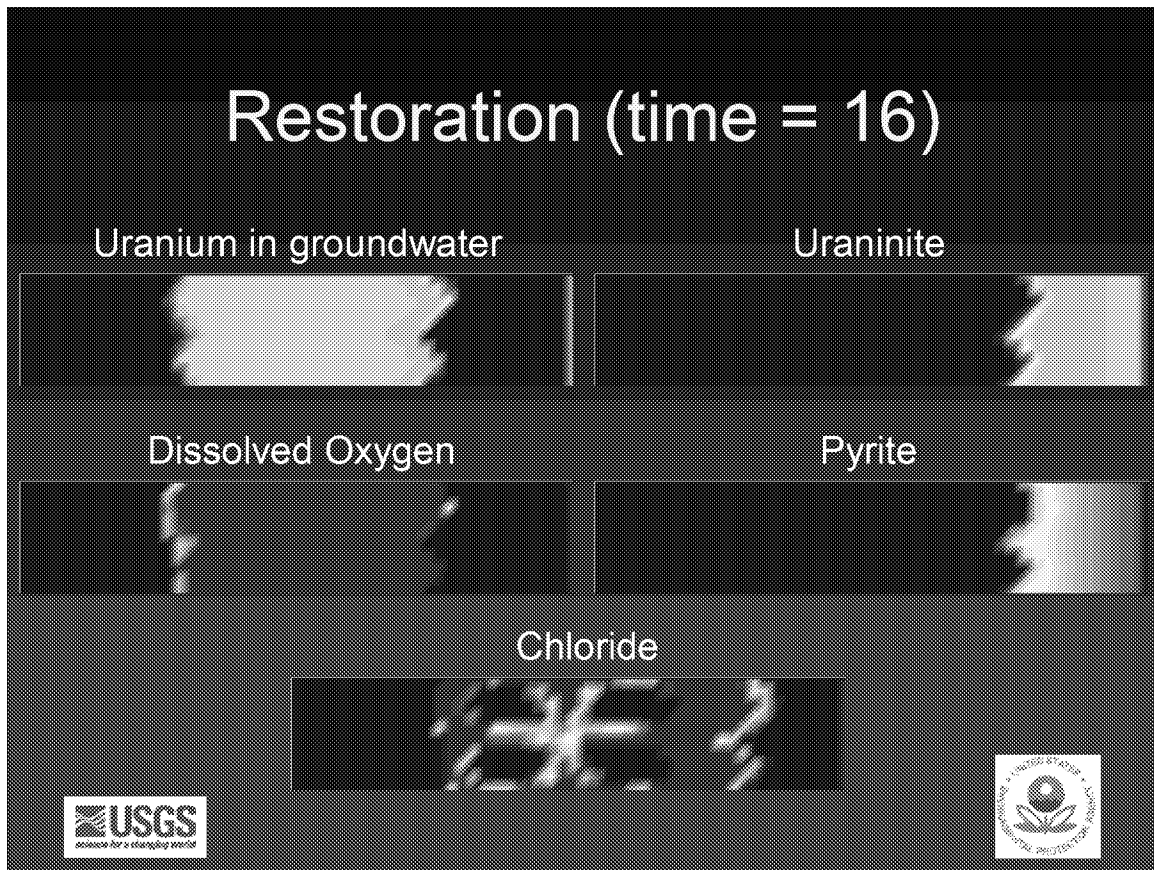
Maximum growth of “clean” restoration fluid. Some chloride is still left due to numerical dispersion.

## Natural Groundwater Flow

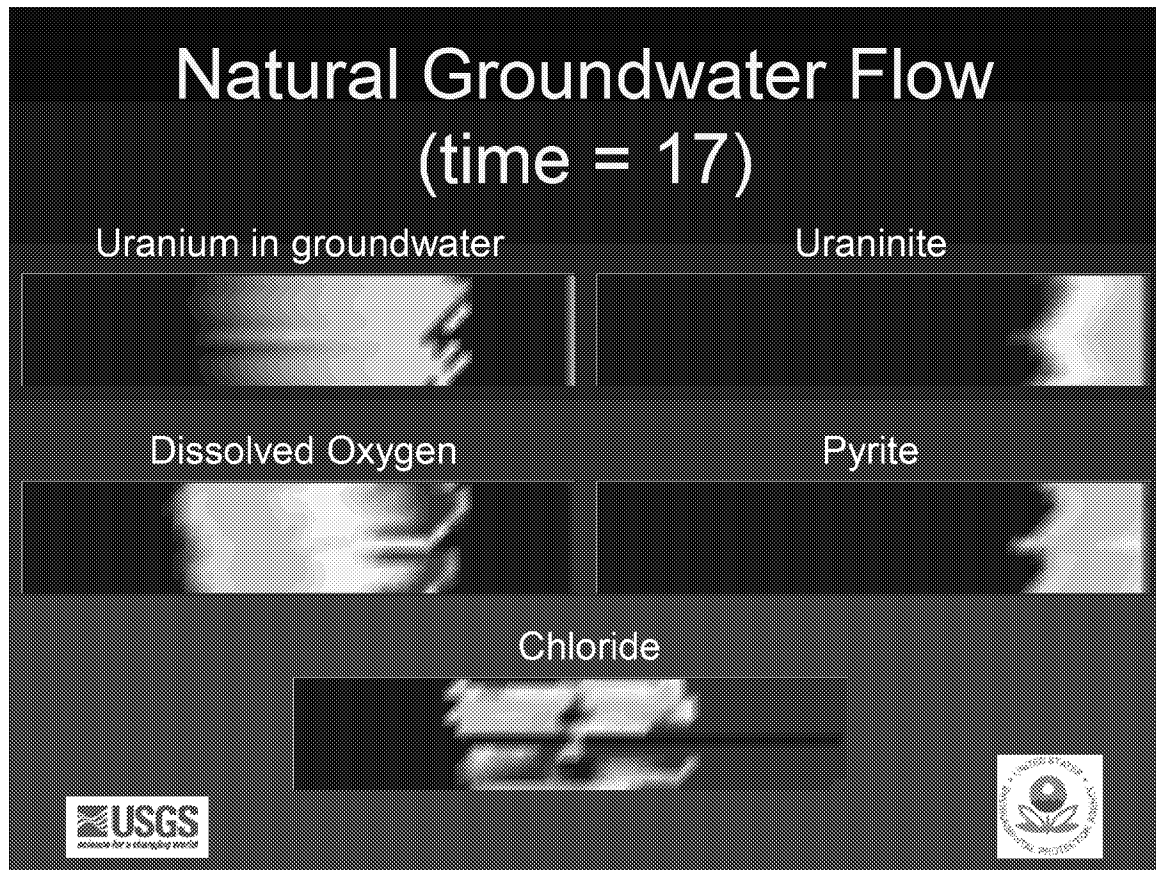
- Use “background” groundwater
- High calcium and sulfate
- No dissolved oxygen
- No chloride



This simulates post-mining and post-restoration as the groundwater flow returns to its natural conditions.

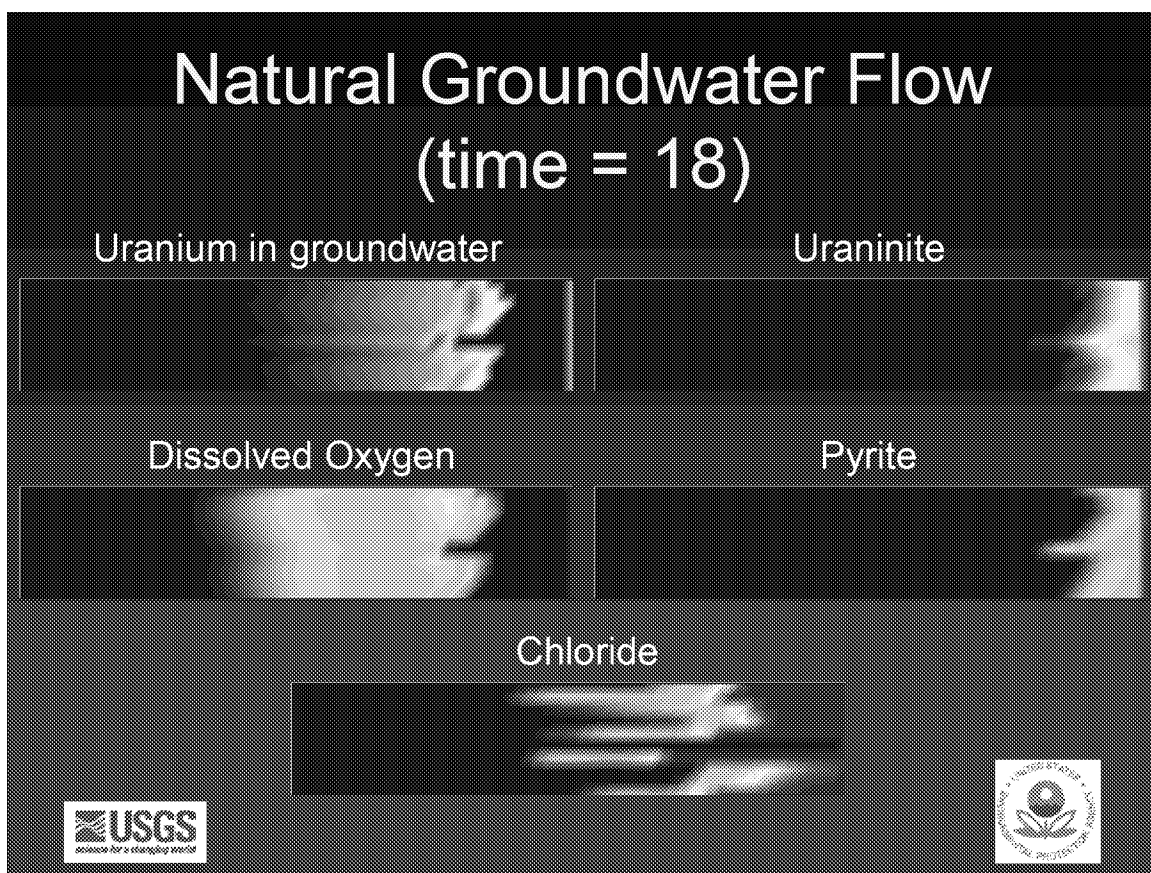


Reminder on where we left off.



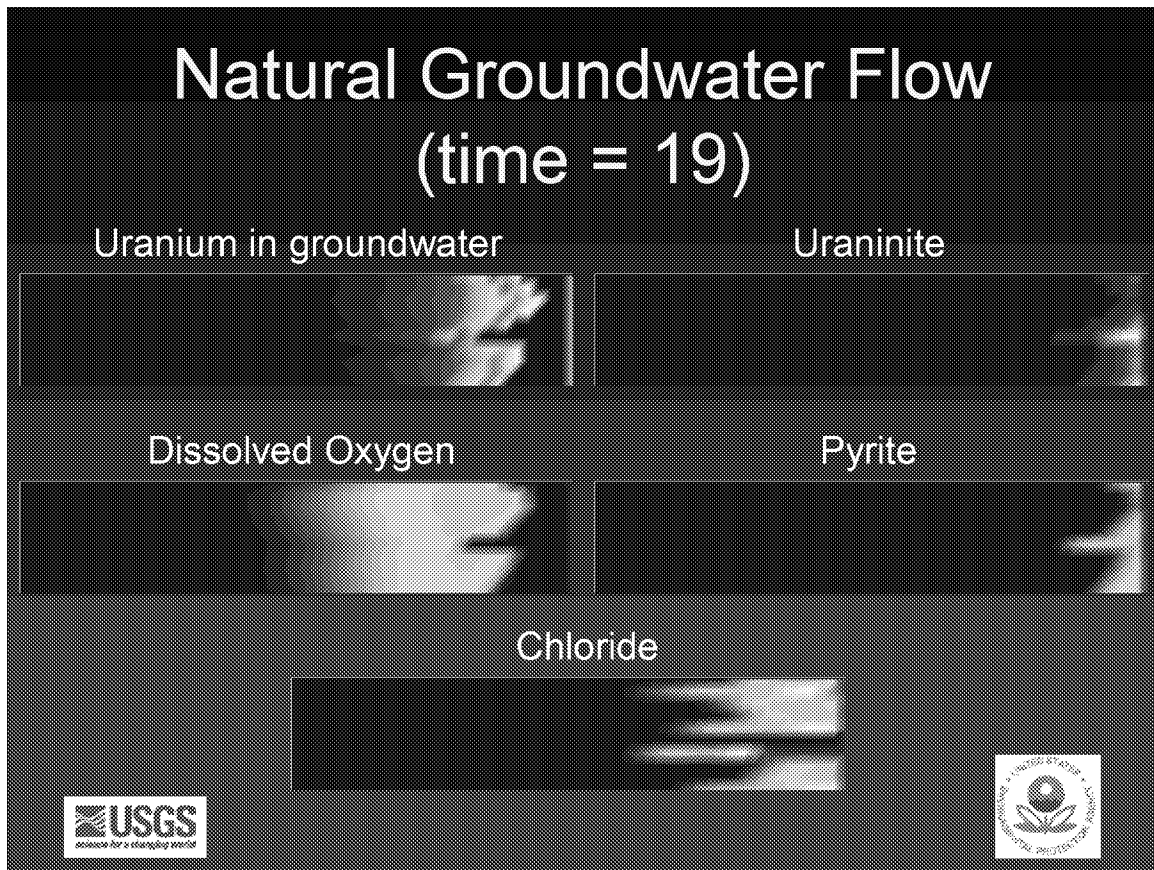
Incoming groundwater on the left side has no uranium, no dissolved oxygen, and no chloride.

This slide series shows how the remaining DO moves the redox front (location of uraninite and pyrite) to the right slightly.

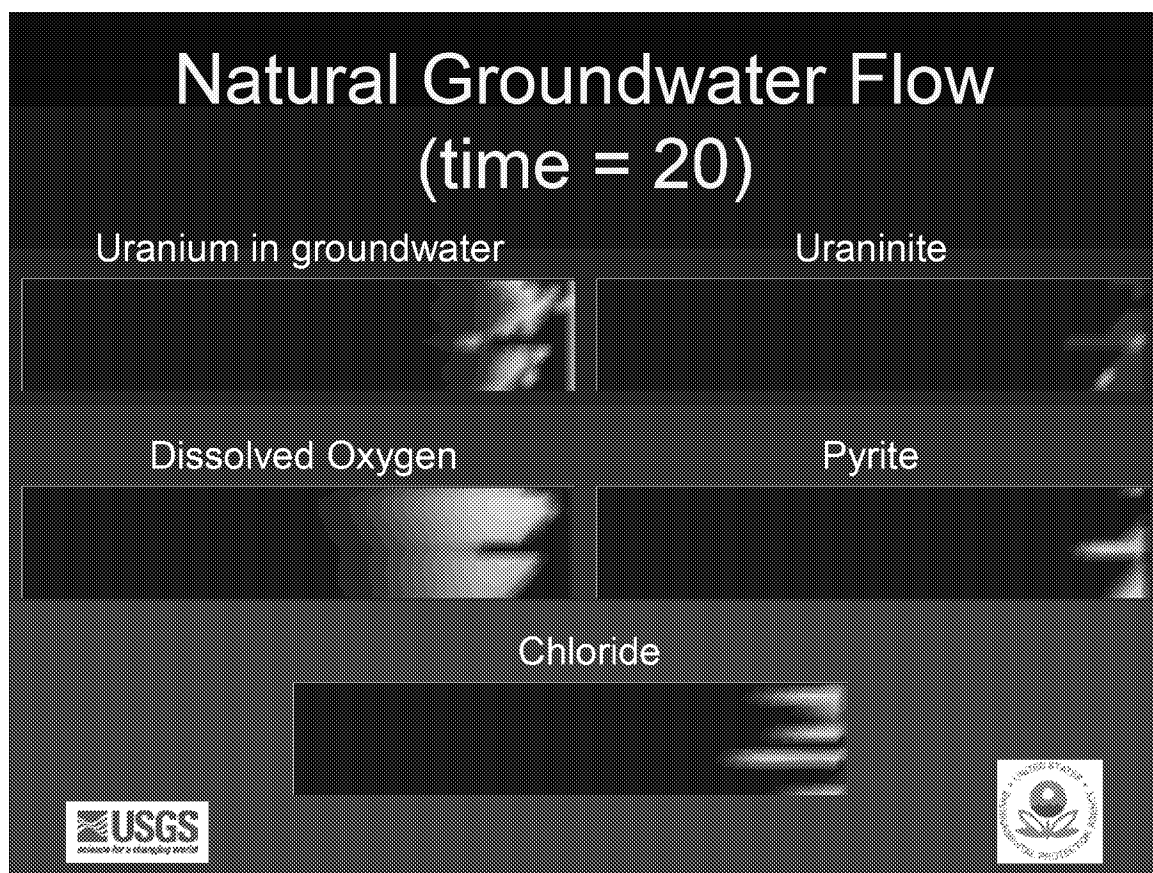


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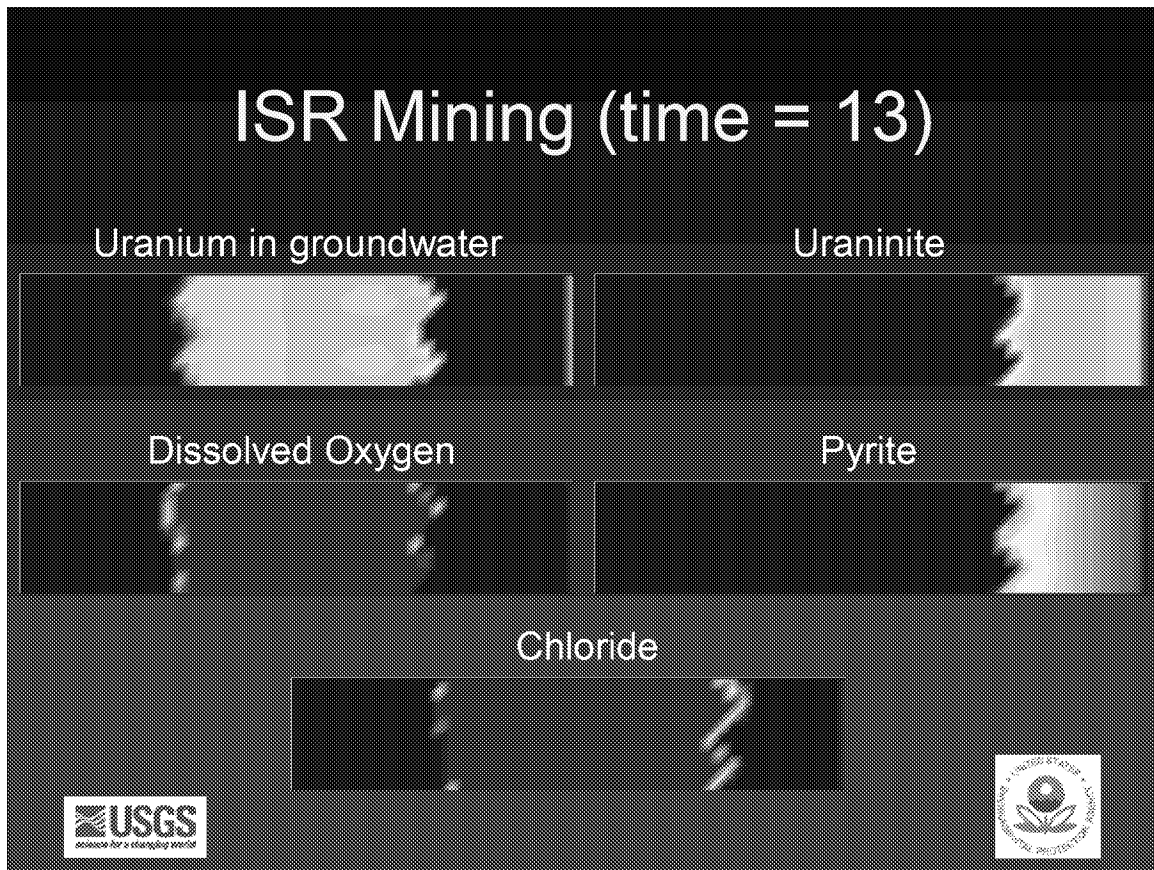
At this time, most of the dissolved oxygen has been consumed with pyrite oxidation, and uranium remains in solution only where DO still exists.

## Restoration no DO

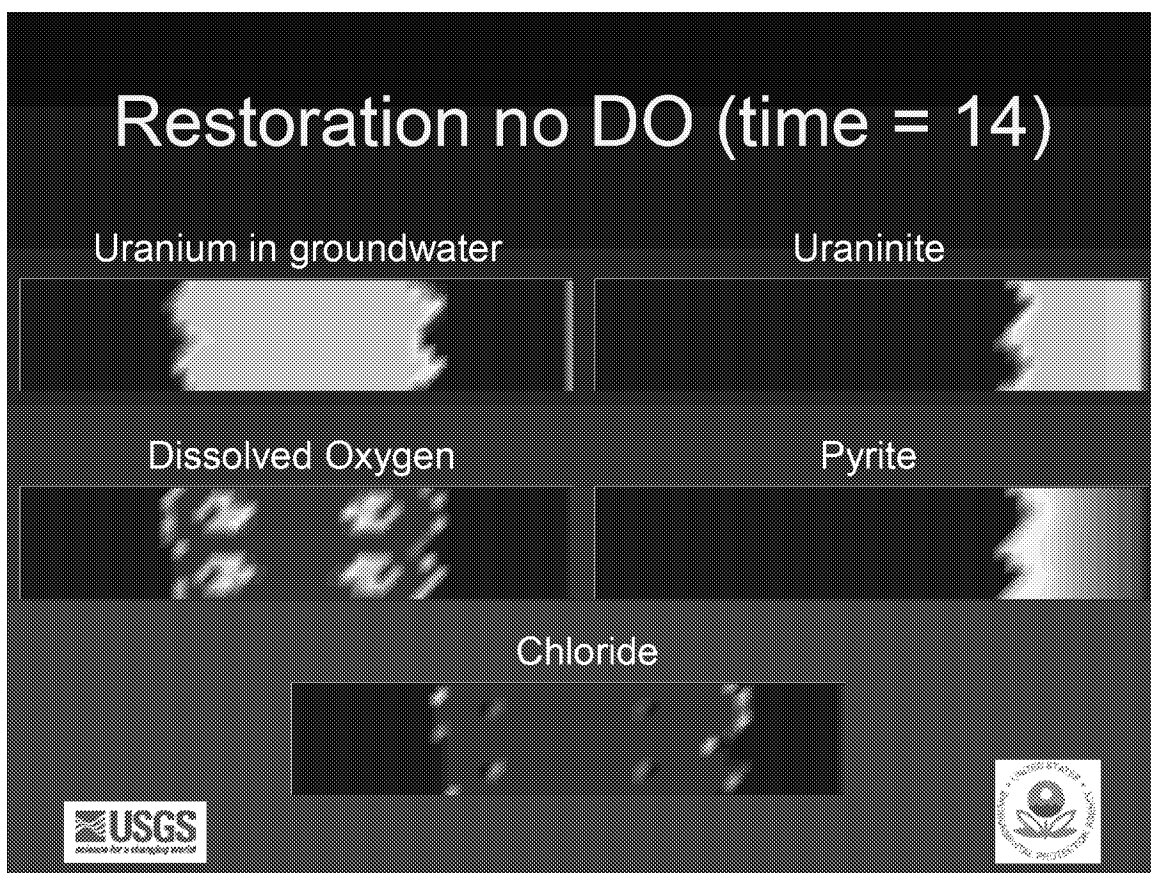
- Flush out mining zone
- Recirculate through a reverse osmosis unit
- Low concentrations of everything
- Uranium kept at 50 ppb
- No chloride
- Keep dissolved oxygen (DO) out of the system



In this restoration simulation, the restoration fluid is carefully controlled to keep DO out of solution.

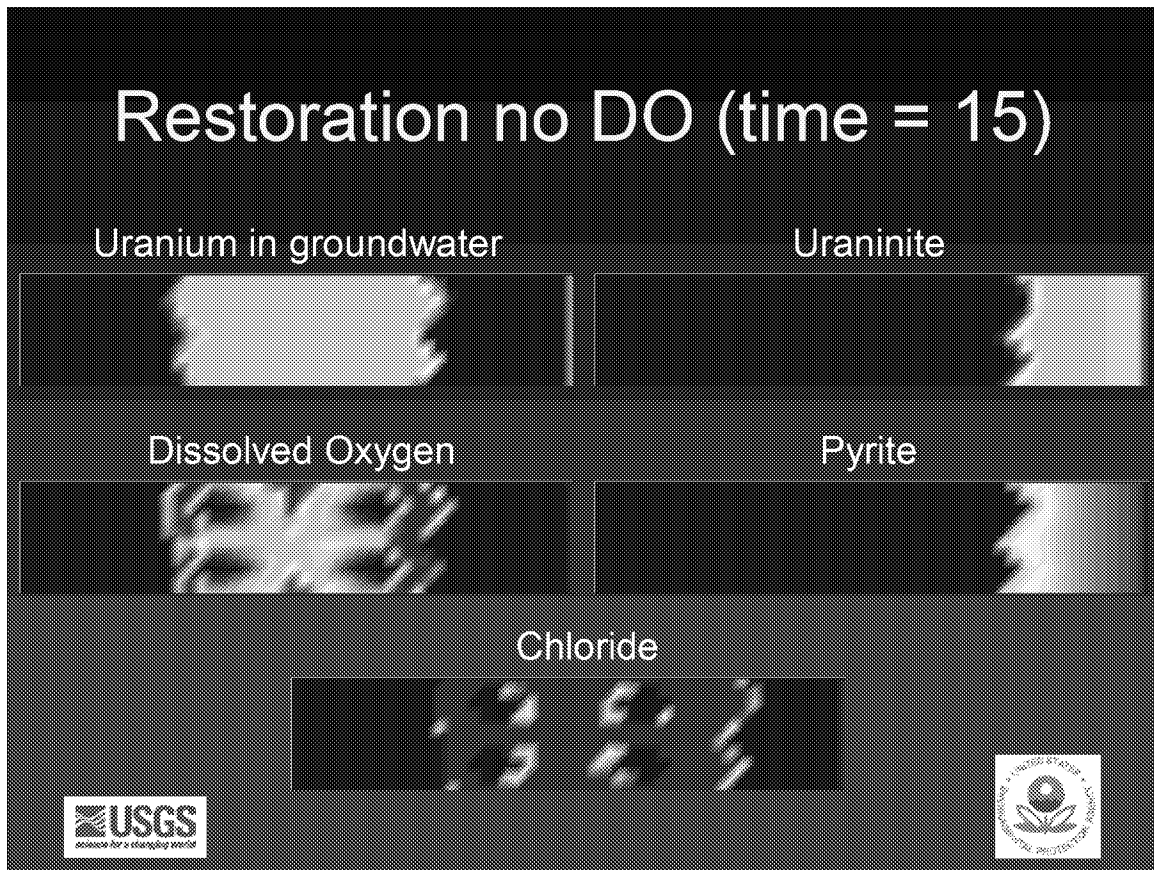


Reminder on where we left off.

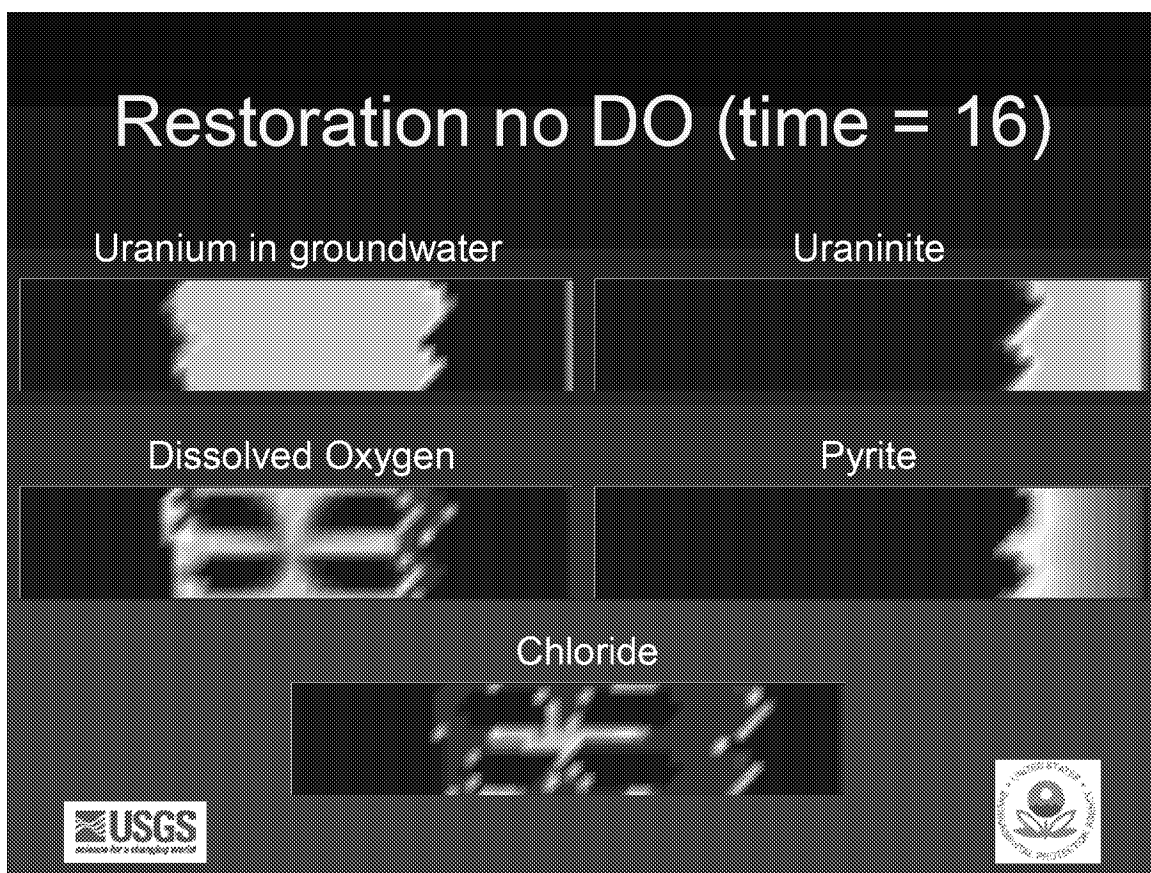


Four-spot pattern now occurs for DO and chloride as both elements are zero in the restoration fluid.

Note that uranium in the restoration fluid is left at 50 ppb, so no four spot pattern.



Slide shows continued restoration.



Slide shows continued restoration.  
Chloride and DO are not fully flushed out due to numerical dispersion.

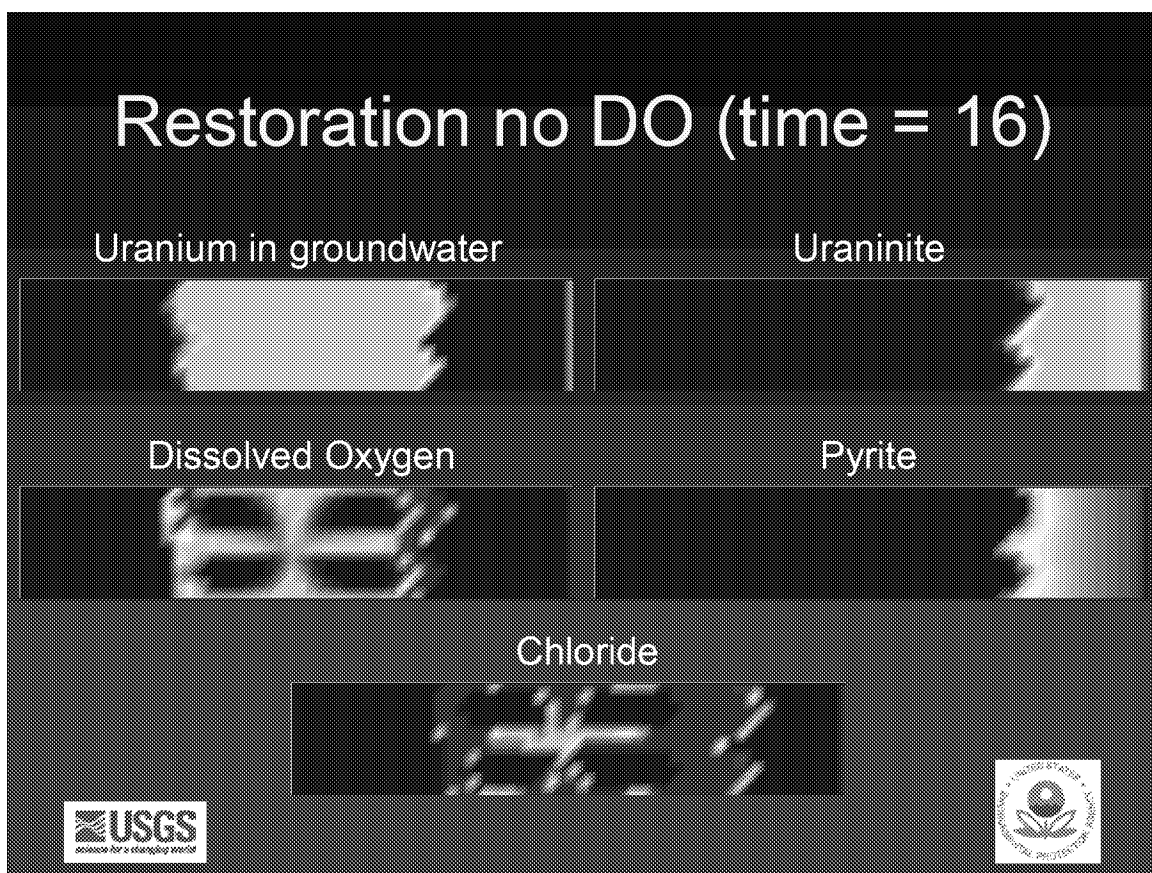
## Natural Groundwater Flow no DO

- Same as before
- Use “background” groundwater
- High calcium and sulfate
- No dissolved oxygen
- No chloride

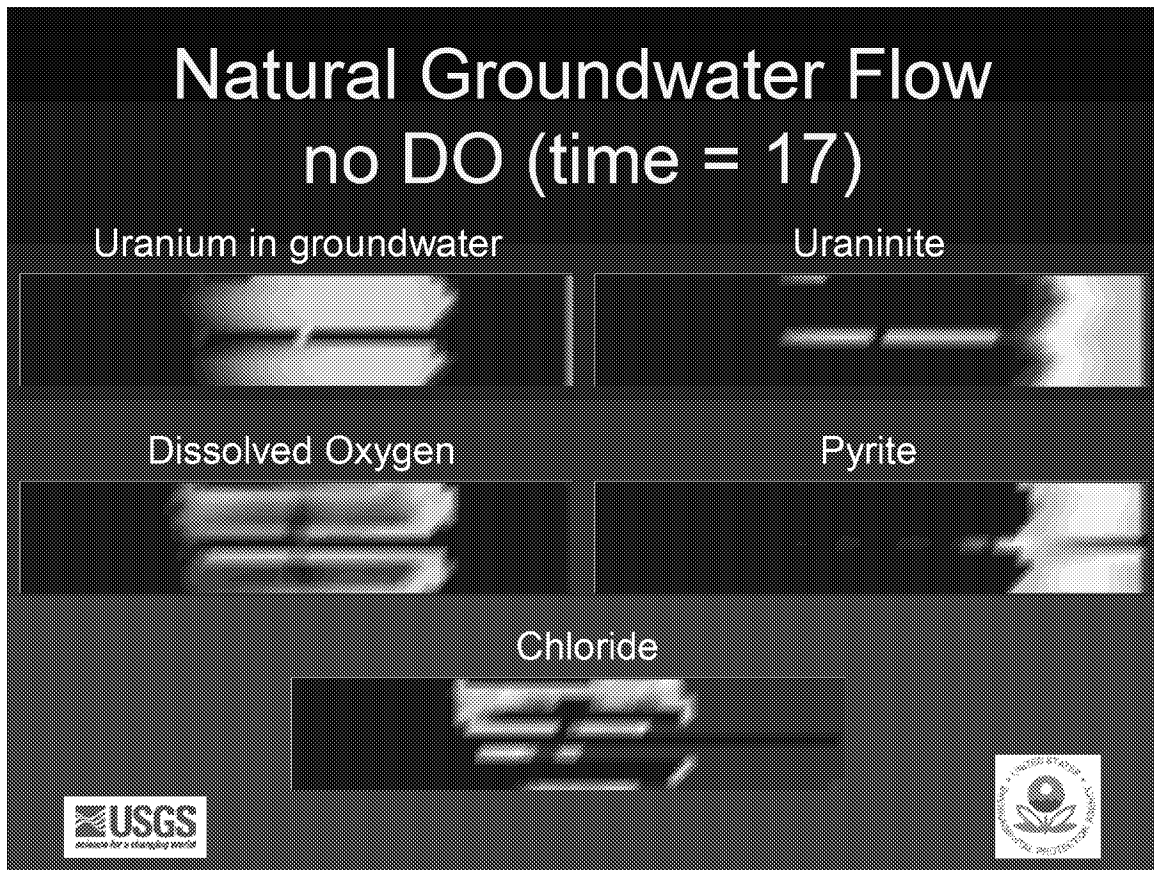


Like before, return the system to “pre-mining” flow conditions.

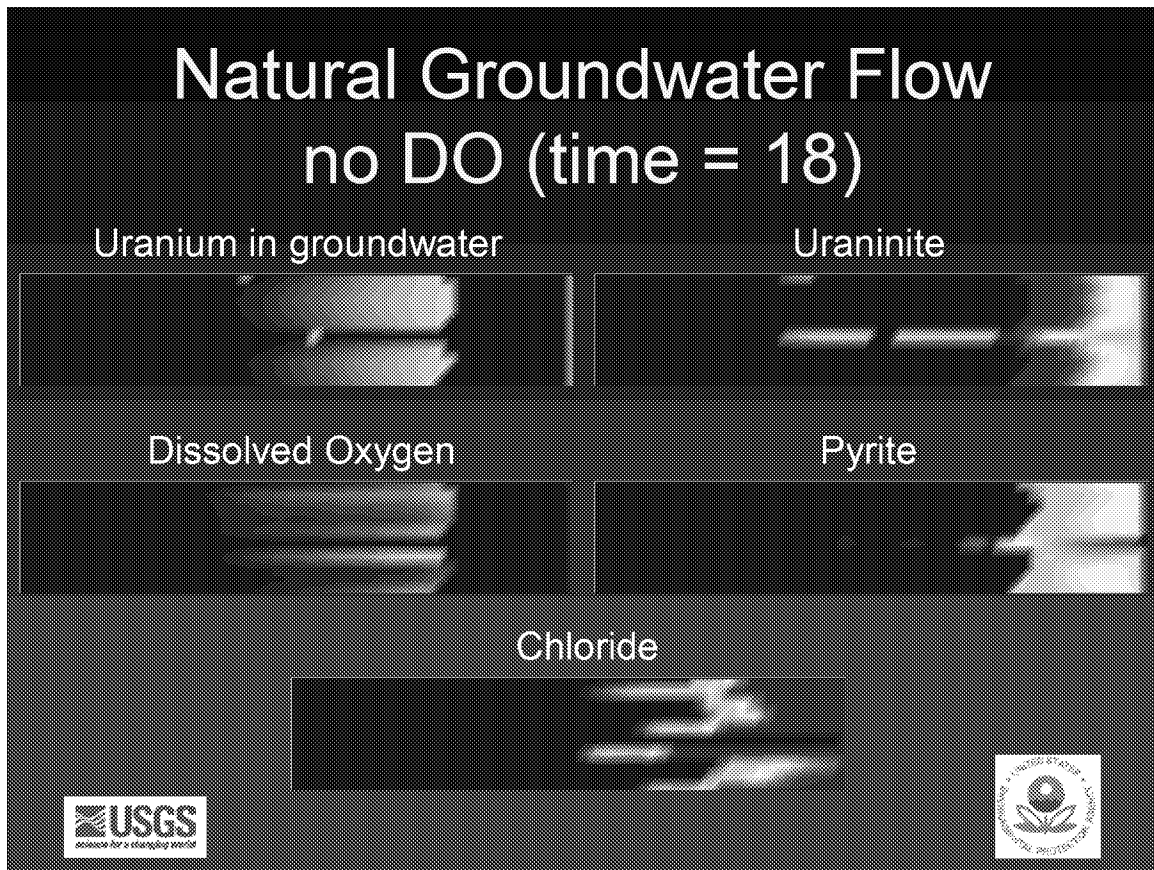


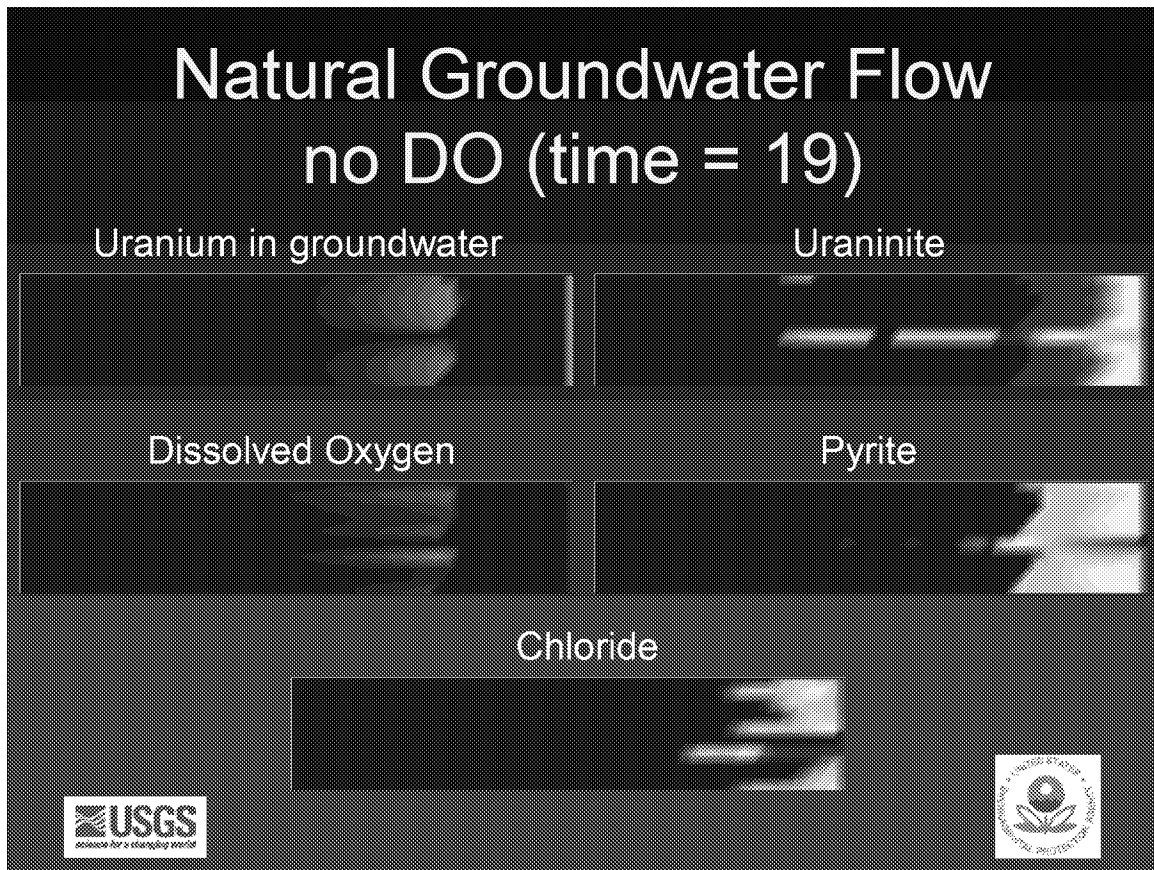


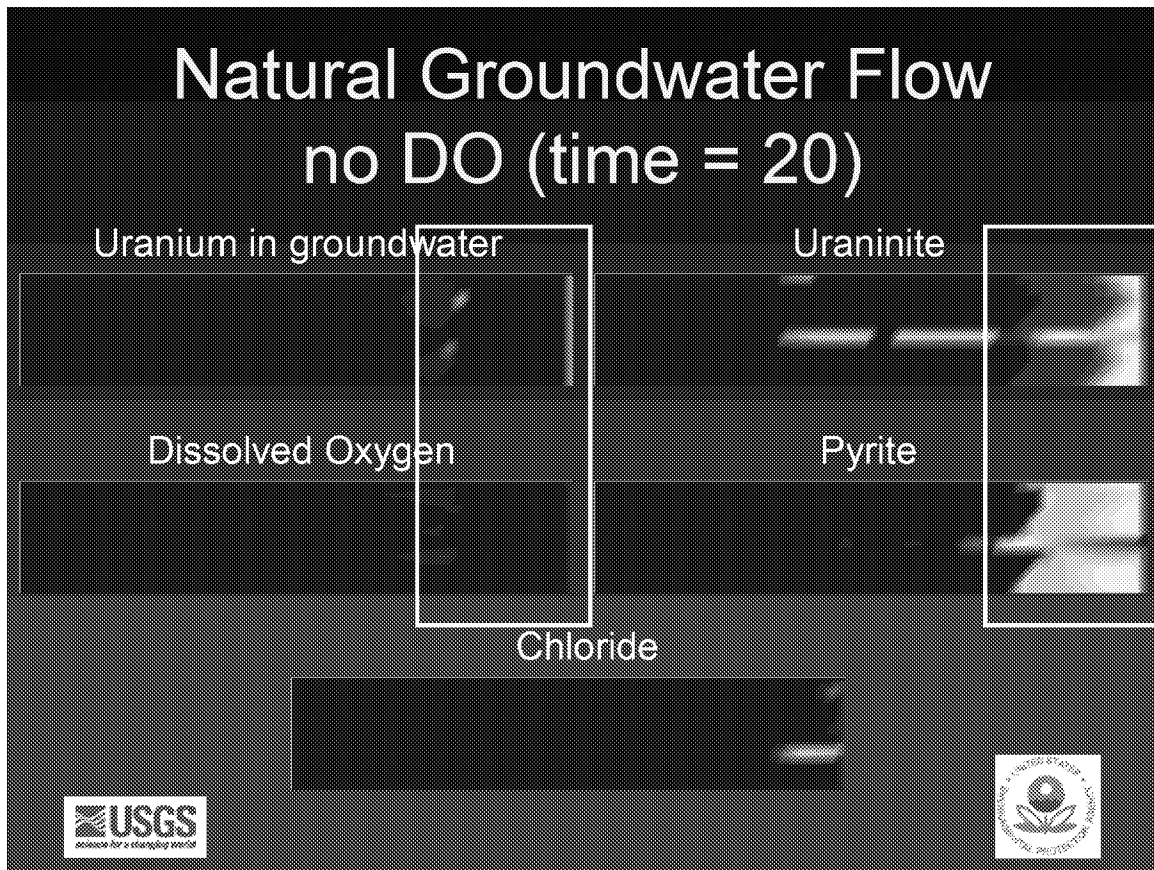
Reminder on where we left off.



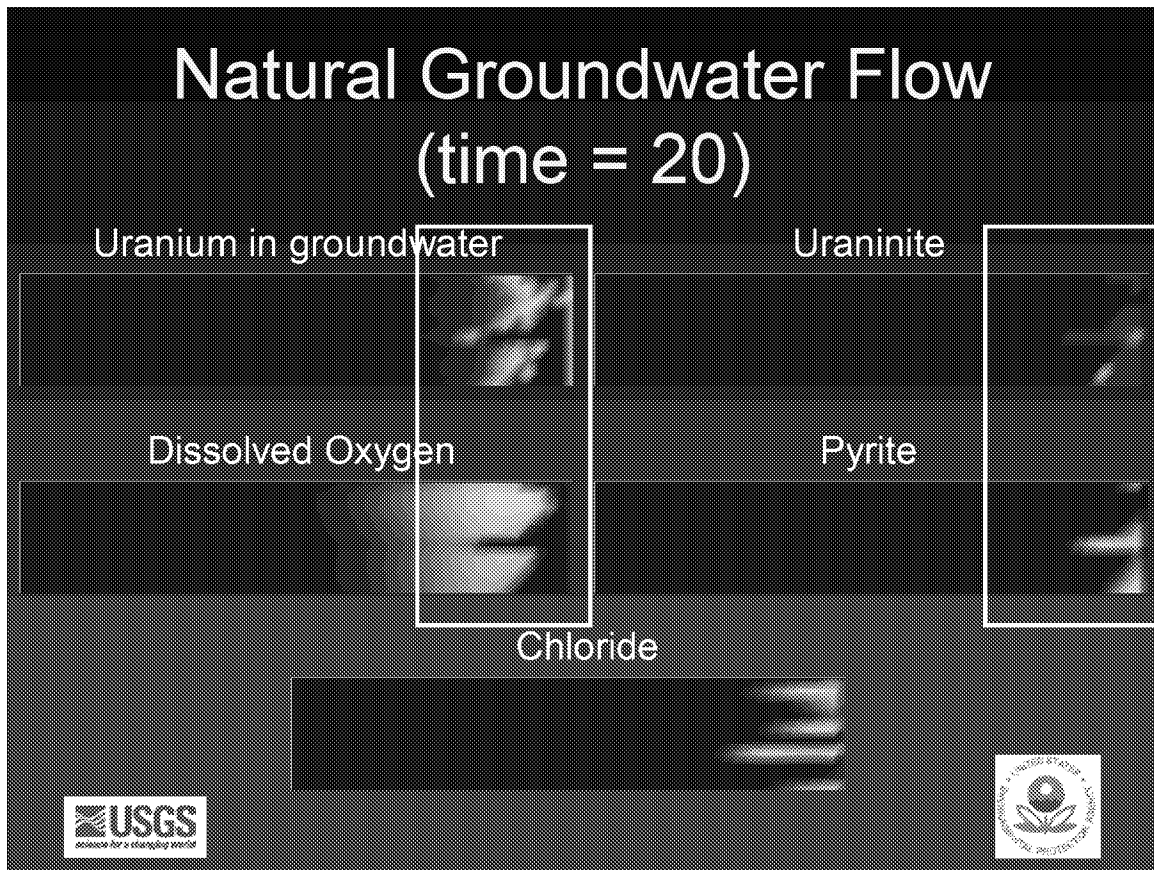
Again, some dissolved oxygen and chloride left in the system due to numerical dispersion.







Next slide will compare this situation/condition with the time=20 step of natural groundwater flow when DO was not controlled.  
Note here that the restoration control with no DO meant that all of the dissolved oxygen was consumed by pyrite, thus allowing for uranium precipitation as uraninite and less overall pyrite oxidation.



See comments in previous slide.  
This slide is the same as slide #46.

## Summary

- Yes, we can simulate the full evolution of roll-front formation, current conditions, ISR mining, restoration, and longer-term transport
- Yes, the simulations can be done quantitatively and in three dimensions
- Yes, reactive transport modeling can be used as a tool to test restoration schemes and the influence on longer-term geochemistry



## Conclusions

- Model calibration and quantitative refinement will be the true test of how well we can simulate these systems (future talk)
- These procedures are applicable to any ISR site, not just the Dewey Burdock site





## Questions?

